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A. G. Eggers, P. S. Hughes, R. F. Lampe,
M. H. Lipner, and J. R. Schornhorst
Westinghouse Electric Corporation
Advanced Energy Systems Division

August 1980

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-163

for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Energy
Office of Solar Power Applications

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Conservation and Solar Energy
Office of Solar Power Applications
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ABBREVIATIONS AND ACRONYMS

A/D	Analog to Digital
AESD	Advanced Energy Systems Division (Westinghouse)
AISC	American Institute of Steel Construction
ANSI	Amercian National Standards Institute
CB	Circuit Breaker
CCW	Counterclockwise
CRT	Cathode Ray Tube
CT	Current Transformer
CW	Clockwise
DOE	Department of Energy
ERDA	Energy Research and Development Administration
FAA	Federal Aviation Administration
FM	Frequency Modulation
FMEA	Failure Modes and Effects Analysis
HAWT	Horizontal-Axis Wind Turbine
HVAC	Heating Ventilating and Air Conditioning
IEEE	Institute of Electrical and Electronic Engineers
I/O	Input/Output
LAS	Lockheed Aircraft Services
LeRC	Lewis Research Center (NASA)
MCP	Motor Circuit Protector
MOSTAB	MOdular STABility Derivative Program
MOSTAB-WT	MOdular STABility Derivative Program - Wind Turbine
MOSTAB-WTE	MOdular STABility Derivative Program - Wind Turbine Empirical
NACA	National Advisory Committee for Aeronautics (now NASA)
NASA	National Aeronautics and Space Administration
NASTRAN	Title of general purpose system computer program used for wind turbine analyses
NEC	National Electrical Code
NEMA	National Electrical Manufacturers Association
OCVR	Overcurrent Voltage Restraint Relay
OSHA	Occupational Safety and Health Administration
OSS	Overspeed Switch
PIV	Portable Instrument Vehicle (Mobile Data System)
PROP	Title of FORTRAN computer program for the determination of performance, loads, and stability derivatives of wind turbines
PT	Potential Transformer
RCMS	Remote Control and Monitoring System
REA	Rural Electrification Administration
RFP	Request for Proposal
RMU	Remote Multiplexer Unit
RPR	Reverse Power Relay
SAIR	Stand Alone Instrument Recorder
VAR	Volt Amperes Reactive
WHM	Watthour Meter
WTG	Wind Turbine Generator

SUMMARY

This report documents the design, analysis, testing, installation, and initial operating performance of the MOD-OA 200 kW wind turbine generator installed at Clayton, NM. The MOD-OA wind turbine was designed and built by the NASA Lewis Research Center for the U.S. Department of Energy as part of the Federal Wind Energy Program. The objective of the MOD-OA project is to obtain early operation and performance data and experience with horizontal-axis wind turbines in utility environments. This report covers the effort from the formation of the MOD-OA project in 1975 to March 1978, when the first MOD-OA wind turbine was released to the Town of Clayton Light and Water Plant for utility operation.

This report contains the NASA project requirements and approach, system description, system design requirements, design and analysis, system tests and installation, safety considerations, failure modes and effects analysis, data acquisition, and initial operating performance for the MOD-OA wind turbine. The system description provides an overview of the mechanical and electrical components. The system design requirements provide the basis for the design.

The design and analysis section of the report includes the requirements, approach, selected design, and supporting analytical results for the components and systems. These components and systems are the rotor and pitch change mechanism, drive train, nacelle equipment, yaw drive mechanism and brake, tower and foundation, electrical system and components, and the control systems. The rotor consists of the blades, hub, pitch change mechanism, and its hydraulic system. The drive train includes the low speed shaft, speed increaser, high speed shaft, belt drive, fluid coupling, and rotor brake. The section on the tower and foundation also describes the service stand and the equipment and personnel hoist. The electrical system and components are the generator, switchgear, transformer, utility connection, and slip rings. The control systems are the blade pitch, yaw, and generator control, and the safety system. The methods and equipment used for manual control, automatic control, and remote control and monitoring are described. The results of system dynamic loads analyses and fatigue analyses are presented.

System tests were performed at NASA and at the site. The engineering data acquisition system includes the instrumentation, remote multiplexer units, mobile data system, and a stand alone instrument recorder. Finally, the initial operating performance from November 1977 through March 1978 is reported.

From the design, analysis, and initial operation (prior to its release for utility operation) of the MOD-OA at Clayton, the following principal conclusions are reached. General agreement is shown between predictions and initial operational measurements for the power output as a function of wind speed and for the structural performance. Satisfactory initial operating characteristics in a utility environment are demonstrated.

INTRODUCTION

HISTORY AND BACKGROUND

Wind energy systems have been utilized for centuries as a source of power for a variety of applications.[1*] Some of the more recent applications included sailing ships for transportation and wind turbines (windmills) for grinding grain, pumping water, and generating electricity. In the early 1940's, a Smith-Putnam large Horizontal-Axis Wind Turbine (HAWT) was designed and built to feed power into the existing electrical network of the Central Vermont Public Service Company. This machine consisted of a two-bladed 175 foot (53.3 m) diameter rotor which was capable of producing 1.25 MW of power. In addition, Dr. U. Hütter designed and built a 100 kW Wind Turbine Generator (WTG) in West Germany in the late 1950s and gained operating experience with his machine tied to the utility network.[2*] The Hütter machine used a downwind 112 foot (34.1 m) diameter two-bladed rotor. Several of the design criteria and design features of the Smith-Putnam and Hütter WTGs were considered or incorporated into the MOD-0 and MOD-0A HAWTs.

RECENT DEVELOPMENTS

The recent national concern over the increase in energy demand and costs of fossil fuels, the dwindling supplies of domestic gas and oil, and the nation's increasing dependence upon imported oil have made it necessary to develop alternate energy sources. Wind energy conversion has long been recognized as a potentially abundant source of electrical power. Utilization of wind energy is becoming more attractive as the cost differential between wind and the more conventional fossil alternatives narrows.

A Federal Wind Energy Program originated at the National Science Foundation in 1973. The objective of this program is to accelerate the development of reliable and economically viable wind energy systems and achieve early commercialization. Satisfying this objective requires advancing the technology, developing a sound industrial base, and addressing the non-technological issues which could impede its development. In January 1975, the responsibility for managing the program was transferred to the Energy Research and Development Administration (ERDA). These efforts were continued by the Division of Distributed Solar Technology in the U. S. Department of Energy (DOE) after October 1, 1977. Recent summaries of the Federal Wind Energy Program have been documented.[3, 4, 5]

One segment of the Federal Wind Program is the development of large horizontal-axis WTGs.[4, 6] In 1973, the NASA Lewis Research Center (LeRC) was asked by the National Science Foundation (and later by ERDA and DOE) to develop, and provide project management for, the designs of large, experimental,

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* NOTE: Superscript numerals refer to the reference number listed in Section 10.0, References and Bibliography.

horizontal-axis WTGs and perform the necessary supporting research and technology development. Initially, a review of prior experience in WTGs was performed.[2, 7] Then, analytical techniques and computer codes were developed to predict the structural dynamics of large HAWT systems. Also, analyses and tests were performed on wake interaction and tower shadow effects, and analytical optimization techniques were developed. Summaries of some of these aspects of technology development have been recently documented.[8, 9, 10]

MOD-O WIND TURBINE GENERATOR

As part of the federal wind program, NASA LeRC designed, built, and started testing a 100 kW wind turbine in September 1975. This experimental project, designated the MOD-0, had primary objectives of providing engineering data and serving as a test bed for evaluating advanced wind turbine design concepts. The MOD-0 WTG was designed using available technology and "off-the-shelf" components where possible. Design, fabrication, and assembly were completed in 18 months. The MOD-0 WTG has a 125 foot (38.1 m) diameter downwind rotor which rotates at 40 rpm. The rotor drives a 60 Hz synchronous alternator through a step-up gearbox at 1800 rpm. Various aspects of the design, analysis, and performance of the MOD-0 WTG were documented.[11, 12, 13, 14, 15, 16, 17, 18]

The MOD-0 project has been used to help understand the performance and the dynamic behavior of wind turbines. The MOD-0 WTG was utilized to: 1) understand the tower shadow and wind shear effects; 2) assess operational performance; 3) evaluate automatic startup and shutdown capabilities, including synchronization to a large and small utility network; and 4) test various components, such as induction generators and steel spar wind turbine blades.[19]

MOD-OA WIND TURBINE GENERATOR

The MOD-OA 200 kW wind turbine generator is, in most respects, an uprated version of the MOD-0 100 kW WTG. The MOD-OA WTG was designed and analyzed by the NASA LeRC for the DOE. The objective of the MOD-OA Project is to conduct early testing of wind turbines in utility environments so that the machine operating performance and dynamic characteristics can be determined. Besides gaining operational experience with wind turbines interfaced with utility networks, an additional objective of the -OA project is obtaining the utility's and the public's reaction to intermediate size WTGs. The prototype MOD-0 design was simplified and made "field-worthy" as it was uprated to the 200 kW size.[20] The status of the MOD-OA project during various phases of its development has been summarized.[17, 21]

The purposes of this report are: a) to document the design and analysis of the MOD-OA 200 KW wind turbine generator at Clayton, NM and b) to present results on the inital operation of the WTG from November 1977 to March 1978, when operation by the Town of Clayton Light and Water Plant was started. Accordingly, this design report documents the design requirements and specifications, the detailed design and analysis of all of the components and systems, the systems analyses on dynamic loads and fatigue, the system tests performed, the

installation, the safety considerations and the failure modes and effects analysis, the data acquisition system, and the initial operating performance of the MOD-OA machine at Clayton. This report covers the effort from the formation of the MOD-OA project in 1975 until March 1978.

Shown in Figure O-1 is the MOD-OA wind turbine in operation at the Clayton site. The operational history for the Clayton MOD-OA WTG during its initial phases of use is as follows:

Date	Event
• November 30, 1977	First rotation
• January 19, 1978	First 100 hours (0.36 megaseconds) of operation
• January 28, 1978	Formal dedication of wind turbine
• March 6, 1978	Turned over for operation by the utility
• May 24, 1978	1000 hours (3.6 megaseconds) of operation [94,000 kW-hr (338.GJ)]

A number of other significant milestones have been achieved with the Clayton WTG since May 1978. Several reports have been written on the Clayton wind turbine which encompass time periods subsequent to the March 1978 design and analysis report date. A summary of the first 10 months of utility operation of the Clayton WTG was prepared.[22] A comparison of the MOD-OA WTG design with a different 200 kW wind turbine generator concept has been reported.[63] The status of the overall MOD-OA project, as it relates to the Federal Wind Energy Systems Program, has been reported.[3] In April 1979, a workshop was held at the NASA Lewis Research Center on large wind turbine design characteristics and R&D requirements. At this workshop, several papers that dealt with the MOD-OA design, operating experience, and blade design and evaluation were presented.[4, 6, 10, 23, 24] Most of the above cited references were published subsequent to the March 1978 date for this design and analysis report. However, these references have information which was germane to the MOD-OA design and analysis and they have been cited for this reason.

ADDITIONAL WTG SYSTEMS

Additional federally funded wind turbine generator systems have been placed in operation, are being developed, or are planned for development. Three additional experimental MOD-OA wind turbines have been installed by the Westinghouse Electric Corporation and are now operating on utility networks. A MOD-OA is operating on Culebra Island, Puerto Rico; Block Island, Rhode Island; and Oahu Island, Hawaii. The Mod-1 experimental 2.0 MW wind turbine is now operating at Boone, North Carolina. MOD-1 was developed and installed by the General Electric Company for the NASA LeRC. The status and detailed analysis and design of the MOD-1 WTG have been reported in various sources.[25,26,27,28] The Boeing Engineering and Construction Company is currently developing a 2.5 MW, 300 foot (91.4 m) diameter WTG called MOD-2 for the NASA LeRC.[29, 30, 31, 32] The MOD-5 and MOD-6H projects are planned for the development of advanced large size (> 1.0 MW) and advanced intermediate size (< 1.0 MW), respectively, wind turbines. Also, the Water and Power Resources Service of the

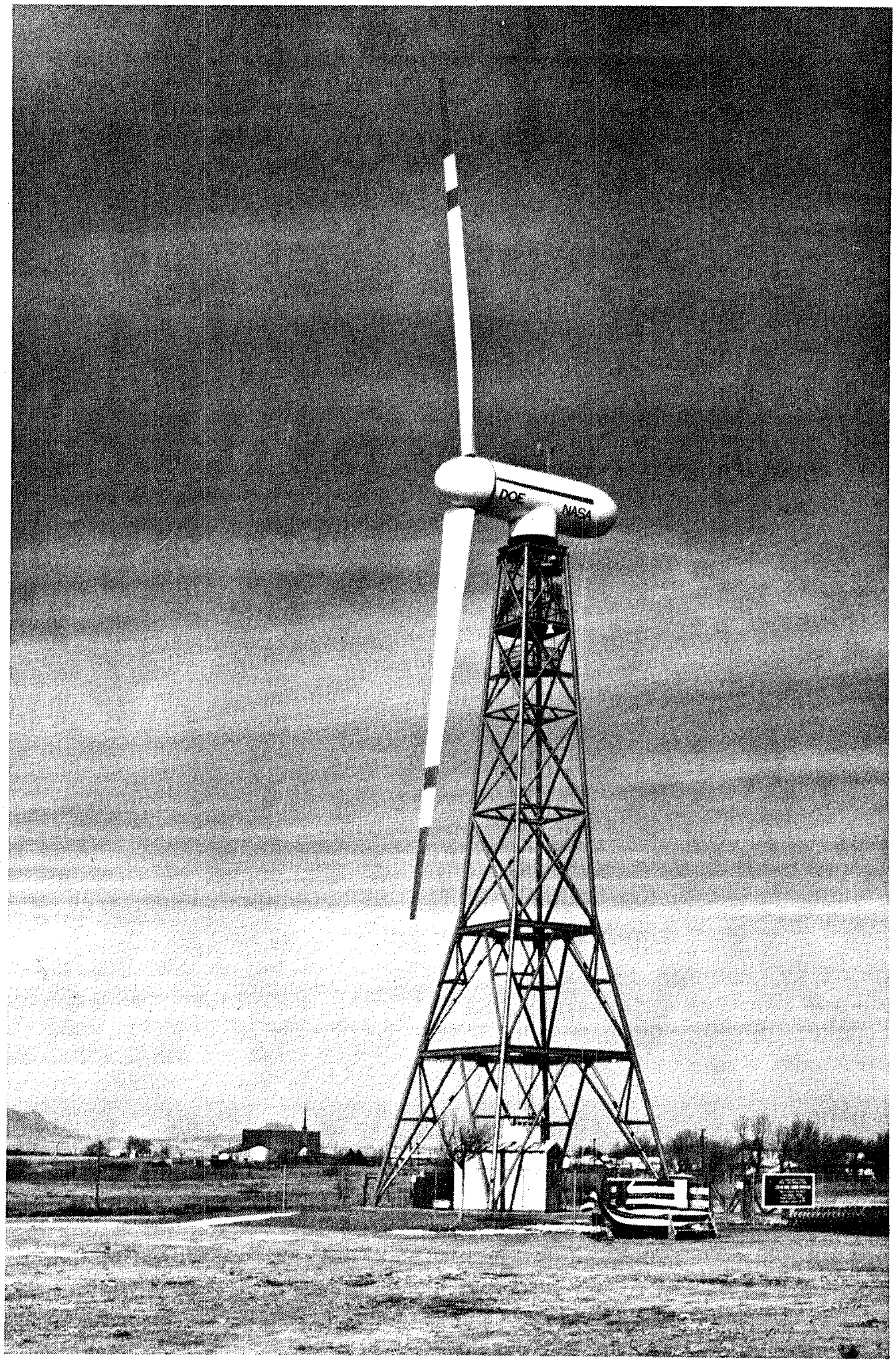

Figure 0-1. MOD-0A 200 kW Wind Turbine Generator; Clayton, NM

U.S. Department of Interior has initiated the development of an additional MW size horizontal-axis wind turbine, designated the System Verification Unit. Each of the additional wind turbine projects was started after the initiation of the MOD-0 and the first MOD-0A wind turbine projects.

SUPPLEMENTARY MOD-0A REPORTS

Two supplementary reports to this MOD-0A design and analysis report have been prepared as part of this contract. An executive summary report on the design and analysis of the MOD-0A WTG has been published.[33] The engineering drawings for the MOD-0A wind turbine have also been documented.[34]

CONCLUSIONS

Several conclusions were drawn by the NASA Lewis Research Center from the design, analysis, and initial operation (prior to its release for operation by the utility) of the Clayton MOD-0A 200 kW wind turbine. These conclusions are categorized into the following: machine performance, structural performance, and utility interface.

In the machine performance area, general agreement was shown between the predicted and measured values for power output as a function of wind speed. The measured drive train efficiency varied with output power and exceeded the design value as the power approached 200 kW. The average cyclic power varied less than ± 20 kW, due to tower shadow and wind shear effects. An ice detector was found to be necessary for safe operation during potential icing conditions.

The structural performance was generally as predicted. Dynamic blade loads measured during initial operation were in good agreement with loads calculated using the MOSTAB computer code. Cyclic loads caused by tower shadow and wind shear were found to be significant and could cause local wear and fatigue damage in the blades and hub. Close monitoring of the blade loads and structural condition, as well as hub clearances, is required to insure structural integrity.

With regard to utility interface, satisfactory operating characteristics in a utility environment during initial tests from November 1977 to March 1978 were demonstrated. The wind turbine was successfully synchronized to the utility network in an unattended mode. The instantaneous frequency was controlled within a peak-to-peak variation of $\sim$1 Hz about the nominal. The wind turbine exhibits a natural mode of oscillation at 1.33 Hz, which is twice the speed of the rotor. Oscillations at this frequency are caused by tower shadow and wind shear effects. Since the dominant frequency of oscillation of the Clayton system is 3 Hz, the wind turbine does not excite the system. As a result of training, utility personnel were able to operate the MOD-0A for the purpose of experimentally supplying power on their utility network.

1.0 PROJECT REQUIREMENTS AND APPROACH

The MOD-OA Project Requirements are presented in Section 1.1. Included are discussions of some of the basic questions that needed to be answered, the overall objectives of the project, the major requirements and objectives (or key issues to be addressed), and a listing of the secondary requirements/ objectives. Presented in Section 1.2 is the approach taken by the NASA LeRC in fulfilling the project requirements. This includes discussions of the management of the project and detailed approach taken, site selection, and project responsibilities.

1.1 PROJECT REQUIREMENTS

Based on the results of prior studies, the major potential contribution of wind power to help solve the nation's energy needs would be in the generation of electrical power for the existing utility networks. This application of wind energy requires large WTGs which will operate in parallel with existing types of power generating equipment, such as diesel-powered or steam turbine generators. Although wind turbines have been built and used in the past in various utility systems, both in the United States and in Europe, no detailed data was available as to how well they performed as part of an electrical power network. Also, the power output of WTGs is dependent on wind speed and the wind is recognized as a variable (fluctuating) power source. At very low wind speeds, no power is produced because there is insufficient energy available in these low winds. Likewise, no power is produced at very high wind speeds [above aproximately 40 mph (17.9 m/s)] because of the cost penalties associated with designing for these high wind conditions and because these conditions occur so infrequently. Finally, for wind speeds where power is usually produced [between about 9 and 40 mph (4.0 and 17.9 m/s)], the (potential) power output varies with wind speed.

These variations of output power raise many technical questions as to how WTGs will operate on a utility network. For example, will the interactions between the WTG and a conventional utility network cause severe electrical and control problems? Will variations in wind turbine power cause excessive current or voltage fluctuations in the main power plant or on the network? Will technical problems result from unattended operation of the WTG? The Department of Energy, NASA LeRC, and the utility companies must have answers to these and other questions before large WTGs can be designed, produced in large quantities, and deployed extensively throughout the U. S. These answers could only come from the operation of several experimental and developmental intermediate and large WTGs in conjunction with utility networks.

Accordingly, the overall objectives of the MOD-OA project, at its inception, were: a) to design, manufacture, install, and operate intermediate size (> 100 kW) WTGs in conjunction with existing utility networks and b) to obtain early operation and performance data on the wind turbine, as well as to gain initial experience in the operation of horizontal-axis WTGs in typical utility environments. In parallel with the MOD-OA and other projects, wind data has been and is being collected at 17 sites throughout the U. S.

Thus, the most significant requirements of the MOD-OA project were:

- To obtain operating experience in utility environments with both small and large utilities to assess the electrical system stability and control requirements

- To determine the impact of a variable power output (due to varying wind speeds) on the utility network, e.g., whether the WTG can be operated in parallel with diesel generators as a supplemental source of power

- To assess the compatibility of the WTG with other utility requirements, e.g., voltage and frequency control of generated power

In addition to the above major requirements or objectives of the MOD-OA project, the following secondary requirements/objectives were delineated:

- Obtain early operation and performance data on the WTG, including dynamic characteristics

- Obtain early recognition and resolution of problems associated with the construction and operation of WTGs in utility systems

- Demonstrate automatic, unattended, fail-safe operation

- Determine the reliability of the MOD-OA machine

- Assess the required maintenance

- Identify and resolve any potential institutional problems in the operation of WTGs at a utility site

- Use the first MOD-OA wind turbine as a test bed, particularly for those items which require long-term operation, for developing improved systems and components

- Develop an experimental WTG which can be used as a research, development, and testing machine

- Identify and incorporate specific design improvements, both in hardware and software, during the two year operating periods for the -OA WTGs

- Develop an industrial capability and interest in the design, analysis, fabrication, and operation of WTGs (necessary to achieve rapid commercialization once the technology has been developed)

- Identify additional utility requirements, including interfaces

- Provide project visibility

- Assess public reaction and acceptance

- Develop expertise by utility personnel in operating and maintaining WTGs

Several of the requirements and objectives which deal with involving utilities in the project were necessary for their future role as successful owners/ operators of wind turbine systems. Some of the above project requirements were delineated and discussed in other reports.[13, 21, 22*]

1.2 APPROACH

1.2.1 MANAGEMENT OF PROJECT AND DETAILED APPROACH

The MOD-OA Project was initiated in January, 1975, significantly before the time the MOD-0 WTG at Plum Brook became operational (the first major power generated by the MOD-0 machine was 80 kW at a rotor speed of 30 rpm on October 23, 1975[14]). Initially, the Energy Research and Development Administration (ERDA) funded the -OA Project and directed the Lewis Research Center of NASA, through an interagency agreement, to expeditiously design and develop an uprated MOD-0 WTG. This responsibility, coupled with the supporting research and technology and other horizontal-axis WTG development efforts at NASA LeRC, came under the direction of the U. S. Department of Energy on October 1, 1977. Thus, ERDA and subsequently DOE directed and provided the sources of funding for the MOD-OA Project, while NASA LeRC participated in the management and executed the design, development, analysis, procurement, fabrication, assembly, shop tests, and installation of the Clayton MOD-OA WTG.

Project management activities by NASA LeRC were directed to satisfying the requirements and objectives delineated in Section 1.1, Project Requirements. By definition, the MOD-OA machine was to be an experimental WTG which could be designed, analyzed, and built expeditiously in order to obtain extensive and early operational experience with intermediate size wind turbines in utility environments. Accordingly, NASA LeRC decided to utilize the basic MOD-0 WTG configuration and uprate that design to as high a power level as practical, while designing and developing the machine on an accelerated schedule. NASA LeRC elected to utilize a rotor configuration basically identical to the MOD-0 machine, i.e., a 125 ft. (38.1 m) diameter rotor using two Lockheed blades. These blades were upgraded from the MOD-0 blades, but very similar in design. Based principally on the constraints of the low speed shaft, rotor, blades, and the speed increaser (gearbox), NASA LeRC selected a power level of 200 kW output at the design wind speed. The major differences between the MOD-0 and MOD-OA wind turbines was that the speed increaser and generator had to be increased in capacity to provide a power output of 200 kW.

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*NOTE: Superscript numerals refer to the reference number listed in Section 10.0, References and Bibliography.

Fulfilling the objective of developing an experimental wind turbine, approximately 100 channels of instrumentation were incorporated into the design in order to collect operating data on the MOD-OA WTG and to learn about structural loads and dynamic behavior. The MOD-OA wind turbine was not optimized for maximum energy production (maximum kW-hr/yr), i.e., no trade-off studies were performed to ascertain whether a 125 ft. (38.1 m) diameter rotor was the best size for a 200 kW WTG at a site with a given average wind speed. On the other hand, a 125 ft. (38.1 m) diameter rotor was considered large enough to represent the dynamics of rotor performance when subjected to the effects of wind shear, tower shadow, coning, and gravity cyclic loads.

Shown in Figure 1.2.1-1 is a comparison of the MOD-0 and -OA output power as a function of wind speed. Although more details on the predicted performance and actual performance of the MOD-OA wind turbine are given in Sections 2.12 and 9.0, respectively, the similarities between the predicted profiles for the two WTGs are demonstrated in this figure. The MOD-0 wind turbine achieves a power output of 100 kW at a rated wind speed of 14.5 mph (6.5 m/s) while the MOD-OA WTG achieves rated power at a 18.3 mph (8.2 m/s) wind speed [both wind speeds measured at a 30 ft. (9.14 m) elevation]. Also, as part of the design approach, NASA LeRC retained a conservative design basis for the MOD-OA WTG. Initially, two machines were planned to be deployed and this was subsequently increased to four wind turbines. A multiple -OA WTG program was pursued to assess the performance of the -OA machines in a variety of applications and different utilities, as well as in a variety of environmental and climatic conditions.

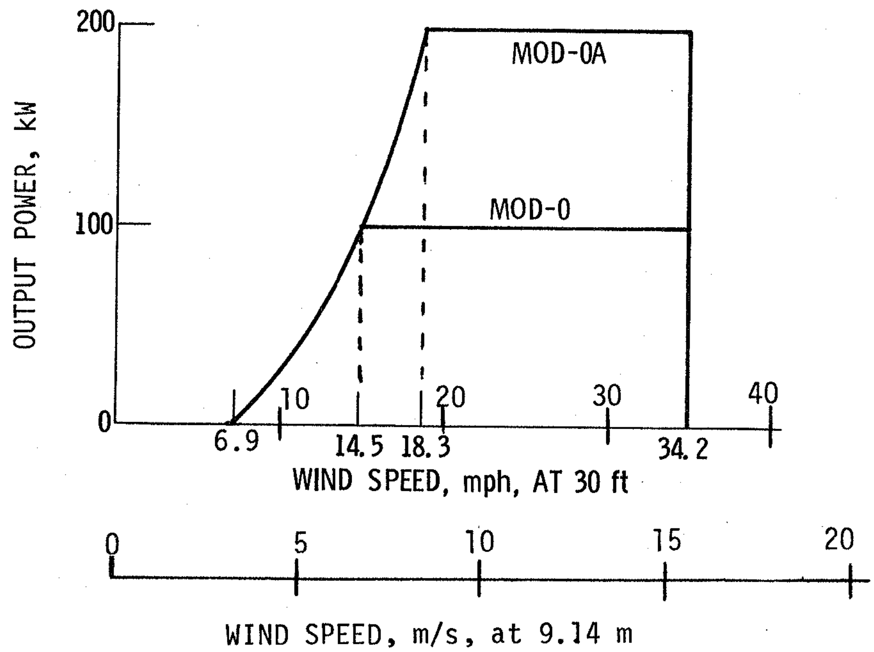


Figure 1.2.1-1. Comparison of MOD-0 and MOD-OA Output Power as a Function of Wind Speed

The detailed approach in the development of the MOD-0A wind turbine was performed in a series of discrete steps, starting with the definition of the system design requirements and ending with the operation of the wind turbine at the utility site.[21] These steps were machine design, design verification, and system assembly and acceptance testing.

The machine design effort was initiated first. The system design requirements were utilized as the basis for the mechanical and electrical design of the -0A WTG. With the definition of the wind criteria and the power output, the mechanical design of the machine was begun. The first step was to define the steady and cyclic loads on the MOD-0A WTG. Definition of loads was recognized as critical throughout the machine and the loads on the rotor were recognized as being especially critical.[9] Therefore, in the development of the MOD-0A wind turbine, careful attention was paid to the loads in the rotor area, because of the critical nature of the blade design. In fact, all computer codes utilized for loads definition were validated by the use of actual measured loads on the MOD-0 WTG. With this technique, NASA LeRC was confident that results could be accurately extrapolated.

In the electrical and control system design area, the machine was designed so that it could be easily synchronized to an electrical power network. This required a control system that automatically starts the machine under the proper wind conditions, brings the machine to the design rotor speed, synchronizes the wind turbine with the utility grid, controls the power level under varying wind conditions, and shuts the machine down during various normal and emergency conditions.

The next step of the detailed approach was the design verification effort. The MOD-0A wind turbine had no formal qualification program for design verification. The mechanical design of the WTG was validated by design analysis, with the analysis tools verified by the MOD-0 test results. The MOD-0 electrical and control systems were basically duplicates of the MOD-0 systems and hence were validated by MOD-0 testing prior to utility operation.

The final step in the approach involved system assembly and acceptance testing. As part of the development of the MOD-0A WTG, the assembly and acceptance testing was accomplished in three phases. The first phase consisted of the assembly and testing of the drive train. The second phase of the assembly and testing process involved the yaw drive assembly, rotor hub, and pitch change hydraulic system, as each of these were added to the power train components. The third phase of assembly and testing occurred at the utility site just prior to on-line operation. This involved the final assembly of the WTG including blades, nacelle, mounting the WTG on the top of the tower, and completing the electrical, controls, and instrumentation wiring. Also, with the use of a mobile data system and the instrumentation and data acquisition system, initial startup and checkout operations were performed and monitored.

1.2.2 SITE SELECTION

As part of the Federal Wind Energy Program, several intermediate to large size experimental wind turbines are being and are to be tested at selected utility

sites. In parallel with the conceptual and detailed design efforts for the MOD-OA Project, a plan was developed for selecting sites for the MOD-OA and other wind turbines. To initiate the site selection process, inquiries were sent in 1974 to many utility companies in the United States. These inquiries described the wind energy program and asked the utilities if they were interested in participating in the program. A meeting was held at the NASA LeRC in December, 1974 with 30 utility companies in attendance.[13]

In the spring of 1976, ERDA issued a request for proposal (RFP) to the utility community to identify high wind sites suitable for testing WTG systems and to identify potential utility interest. This RFP was issued to 3200 utility or electric supplying organizations in the United States[5] which vary in size from very small to very large utilities. In response to the RFP, over 65 utilities went to the trouble of locating sites, submitting detailed information about their company and their site as they proposed them to ERDA, and stating that they were willing to accept the associated costs of the project. These costs were to include developing the sites, installing the interconnecting wiring, and operating and maintaining the meteorological tower and possibly the WTG that would be located at their site. From the 65 utilities that submitted proposals, 17 sites were selected. These were selected on the basis of maximizing the amount of information for the Federal Wind Energy Program and for the utility industry as a whole. The following site factors and variables were considered during the site selection process performed by and under the direction of ERDA:[13]

- Wind energy available at the site
- Utility's utilization of variable wind power and need for supplemental power
- Mode of power generation (the wind turbine will interface with hydro, steam, diesel, etc.)
- Size of utility company and network
- Cost of competitive power
- Geographical location and environment (including variations in climatic and topographical conditions)
- Project visibility to assess public reaction
- Utility's interest in participating in, and supplying personnel for, the program

At each of the 17 sites, ERDA installed identical meteorological towers and instrumentation to measure site wind data, so that the wind potential of the sites could be evaluated on a commom basis.* The towers were 165 feet (50.3 m)

*Actually, five of the sites: Oahu, HI; Clayton, NM; Ludington, MI; Amarillo, TX; and Boardman, OR; (see Figure 1.2.2-1) were already equipped with adequate meteorological towers, while additional instrumentation was required at some of these five sites.

tall and were equipped with anemometers and wind direction sensors at two altitudes. The towers, instrumentation, and recording equipment were installed and have been and are being serviced by a government contractor. Each of the utility companies was required to install the meteorological tower foundation and to check the tower and recording equipment on a regular basis. Wind data from the towers have been recorded automatically, collected by the utilities, and forwarded to a government contractor. The 17 sites selected for more detailed evaluation are shown and listed in Figure 1.2.2-1, along with the participating utility company.[17]

Initially, two sites were selected to receive MOD-OA WTGs and this was later expanded to four sites. These four sites (see Figure 1.2.2-1) are Clayton, New Mexico, the Island of Culebra, Puerto Rico, Block Island, Rhode Island, and Oahu, Hawaii. At each of these sites, the government is supplying, at no cost to the utilities, the following major items:[13]

- The wind turbine and its foundation
- All necessary controls, instrumentation, and recording equipment
- NASA and NASA contractor personnel for the installation, checkout, non-routine maintenance, and general support during the two year operating period

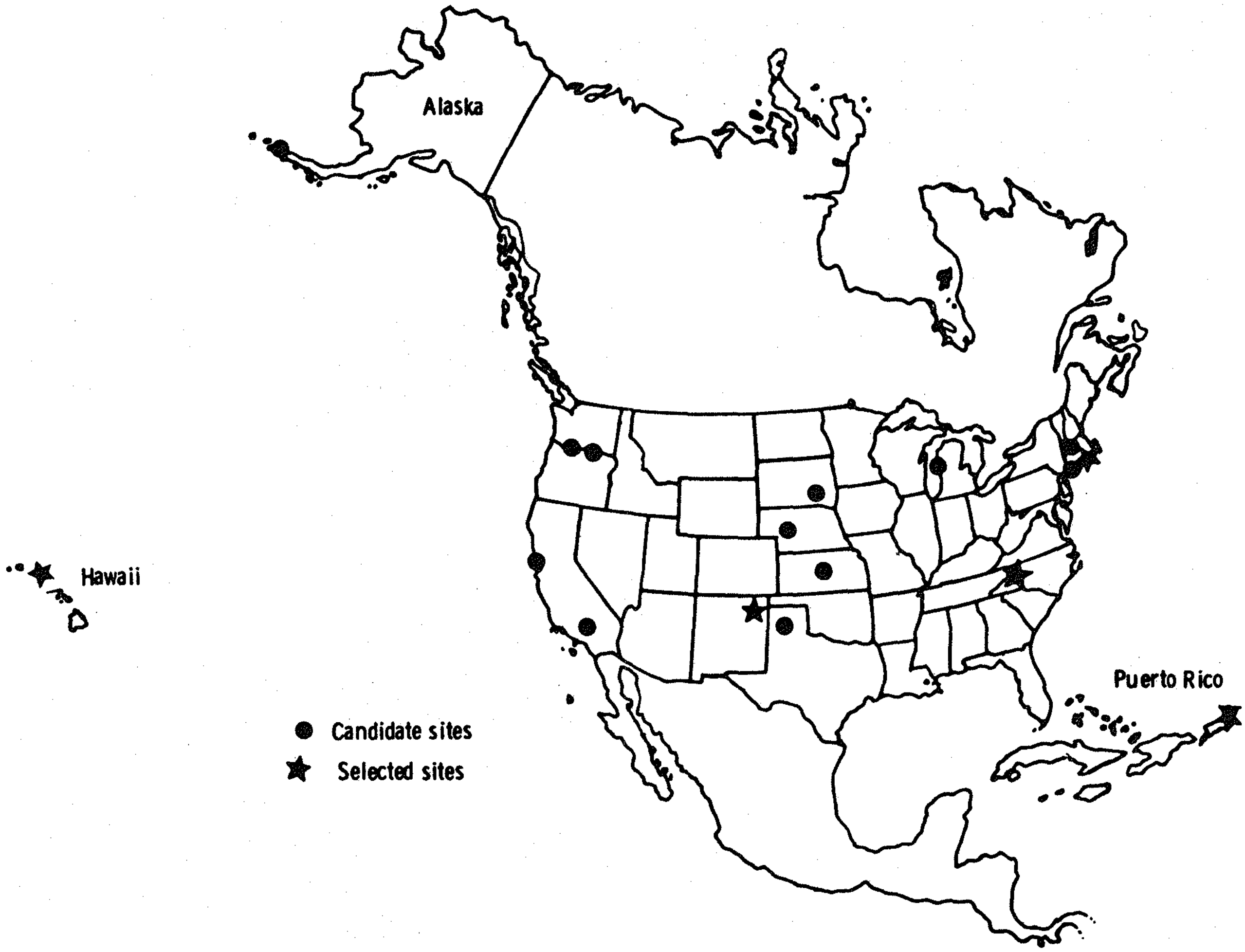
The utility companies are providing the following items at no cost to the government:

- The site on which the wind turbine is located
- Site preparation, including an access road, security fencing, necessary electrical interface equipment, and a remote control room
- Personnel to interface with NASA and the NASA contractor during site preparation, final assembly, and checkout
- Personnel for operating, monitoring, and recording pertinent operating performance data, and for routine maintenance of the wind turbine for up to two years

The fuels used to produce the power for each of the four participating utility companies, along with their peak power demands, are as follows:

Site	Fuel	Peak Power (kW)
Clayton, NM	Diesel/natural gas*	3,800
Culebra, PR	Diesel (backup)*	1,200
Block Island, RI	Diesel*	1,400
Oahu, HI	Oil	900,000

*For reciprocating engines to drive generators.



Site	Organization	Site	Organization
Cold Bay, Alaska	Alaska Bussell Electric Co.	Montauk Point, Long Island, New York	Long Island Lighting Co.
Point Arena, California	Pacific Gas and Electric Co.	Boone, North Carolina[b]	Blue Ridge Electric Membership Corporation
San Gorgonio Pass, California	Southern California Edison	Boardman, Oregon	Portland General Electric Co.
Oahu, Hawaii[a]	Hawaiian Electric Co.	Island of Culebra, Puerto Rico[a]	Puerto Rico Water Resources Authority
Russell, Kansas	City of Russell, Kansas	Block Island, Rhode Island[a]	Block Island Power Co.
Holyoke, Massachusetts	City of Holyoke Gas and Electric Department	Huron, South Dakota	East River Power Cooperative
Ludington, Michigan	Consumers Power Co.	Amarillo, Texas	Southwestern Public Service Co.
Kingsley Dam, Nebraska	Central Nebraska Public Power and Irrigation District	Augspurger Mountain, Washington	Bonneville Power Administration
Clayton, New Mexico[a]	Town of Clayton		

[a]Four sites selected for 200-kW systems (MOD-0A).
[b]Site selected for 2000-kW system (MOD-1).

Figure 1.2.2-1. The 17 Candidate Wind Turbine Sites

Except for Culebra, all utilities are isolated and have no tie with neighboring grids. Culebra just recently installed an underwater cable to bring power from the mainland. The diesel-powered generators which were used previously to provide power now serve as a backup in the event the underwater cable should fail.

The City of Clayton, New Mexico is located in the extreme northeastern corner of the state near the Texas Panhandle area of the Great Plains. The region represents a large geographical area with excellent wind potential. The wind speed at Clayton, NM at hub height is above 8.5 mph (3.8 m/sec) 90 percent of the time[22] and the mean wind speed at the hub is 15 mph (6.7 m/sec). The city has a small municipally owned electric utility system which is capable of operation on natural gas or diesel fuel. The system is independent and interconnection with existing systems is impossible because of existing REA loads. Additional power can only be obtained by negotiation with commercial utility companies and subsequent construction of transmission lines, probably in excess of 62 miles (100 km) in length. An aerial view of Clayton, NM with the MOD-OA 200 kW wind turbine shown in the center foreground is presented in Figure 1.2.2-2. Table 1.2.2-1 summarizes the general characteristics of the city's power usage, population, mean wind speeds, elevation, and temperature.[22] Shown in Figure 1.2.2-3 is an overall view of the Clayton WTG site, including the 160 ft. (48.8 m) tall meteorological tower used to measure site wind data at two elevations.

TABLE 1.2.2-1: GENERAL CHARACTERISTICS OF CLAYTON, NM (POPULATION, ELEVATION, ENERGY CONSUMPTION, POWER DEMAND, MEAN WIND SPEEDS AND TEMPERATURE)

Population	3,000
Elevation	5,000 ft. (1520 m)
Annual Energy Consumption (1978)	15,100 MW hr
Peak Power Demand	3.8 MW
Average Daytime Power Demand	2.8 MW
Mean Annual Wind Speed: (Battelle data for 1979):	
@ 30 ft (9.1m)	12 mph (5.4 m/sec)
@ Hub Height - 100 ft (30.5 m)	15 mph (6.7 m/sec)
Temperature Range	-10°F (-23°C) to +120°F (49°C)

1.2.3 PROJECT RESPONSIBILITIES

NASA LeRC is responsible for managing all phases of the project. One of the secondary requirements/objectives of the project was to develop an industrial capability and interest in the design, analysis, fabrication, operation, and commercialization of WTG systems. Also, NASA LeRC's approach to

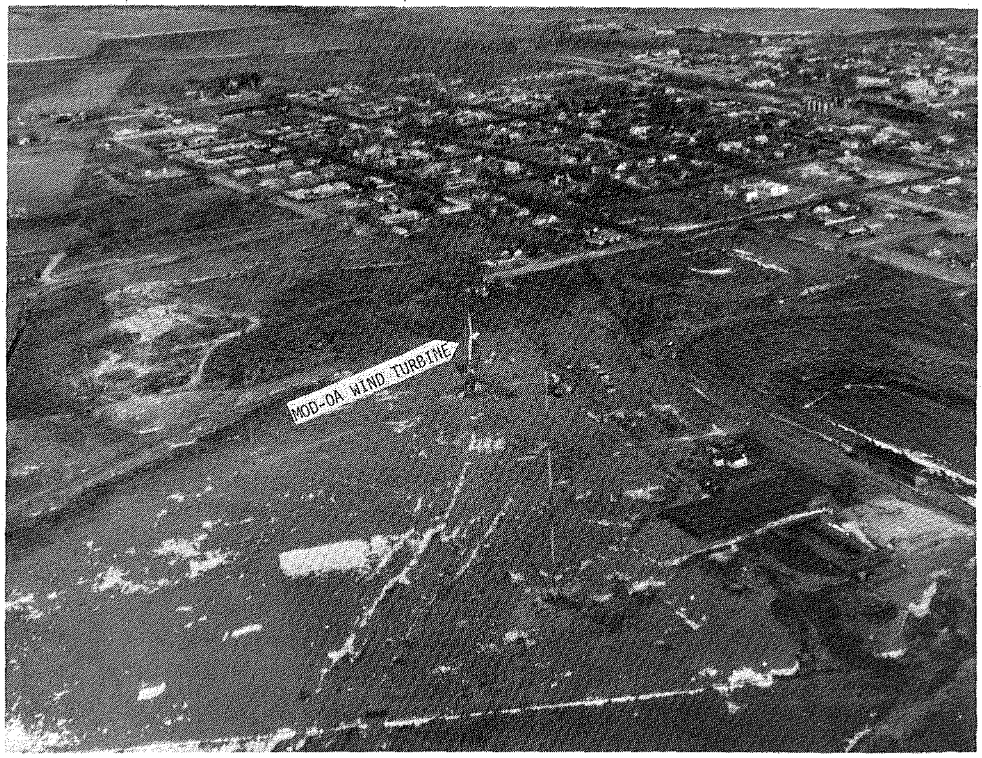


Figure 1.2.2-2. Aerial View of Clayton, NM with MOD-OA 200 kW Wind Turbine

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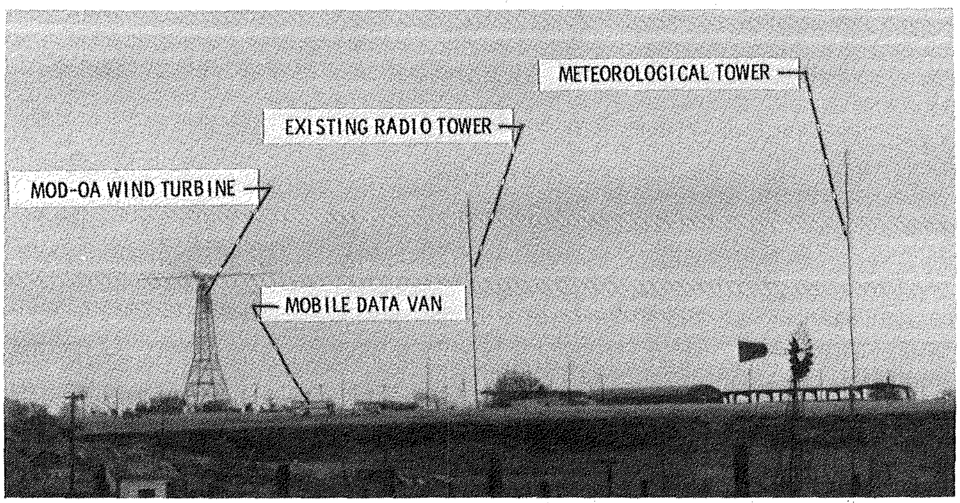

Figure 1.2.2-3. Overall View of Clayton MOD-OA Wind Turbine Site

the project was to expeditiously design, analyze, and build several MOD-OA WTGs. Therefore, NASA LeRC elected to retain the design, analysis, procurement, assembly, and in plant testing responsibilities for the Clayton MOD-OA wind turbine; and gradually involve an industrial contractor with increasing responsibilities as the later MOD-OA wind turbines were to be built. The wind turbine design, component specifications, engineering drawings, supporting analyses, and testing requirements and procedures were established/performed by the NASA Lewis Research Center. In general, this policy prevailed for not only the Clayton MOD-OA wind turbine, but also the subsequent WTGs installed at Culebra, Block Island, and Oahu.

As part of the MOD-O program, the blades for the MOD-OA wind turbine were analyzed and designed by the Lockheed California Company located in Burbank, CA. During the MOD-OA project, NASA LeRC issued a request for proposal to various manufacturers to build the MOD-OA wind turbine blades under a "build to print" contract. The Lockheed Aircraft Service Company located in Ontario, CA was selected for fabricating the MOD-OA blades.

The project responsibilities for each of the four MOD-OA wind turbine sites are shown in Table 1.2.3-1.

TABLE 1.2.3-1: PROJECT RESPONSIBILITIES FOR THE FOUR MOD-OA WIND TURBINE SITES

Wind Turbine Site	Procurement/ Fabrication	Assembly/ Shop Test	Installation
Clayton, NM	NASA LeRC	NASA LeRC	Contractor*
Culebra, PR	NASA LeRC	Contractor	Contractor
Block Island, RI	Contractor	Contractor	Contractor
Oahu, HI	Contractor	Contractor	Contractor

* Westinghouse Electric Corporation

The Special Services Division, Industry Services Divisions, of the Westinghuse Electric Corporation was selected by competitive bid to be the overall systems contractor for the MOD-OA project. For the Clayton wind turbine, NASA LeRC performed all of the procurement, fabrication, assembly, and shop testing of the WTG prior to its installation. Both NASA LeRC and Westinghouse personnel have been involved in the installation and checkout operations for each wind turbine. The increasing levels of responsibility which have been assumed on subsequent MOD-OA WTGs by the contractor (Westinghouse) are also shown in Table 1.2.3-1. During the installatin of each of the -OA WTGs, a series of site tests and initial performance evaluations are completed. Finally, NASA LeRC and the Westinghouse Electric Corporation (including the Advanced Energy Systems Division) were jointly involved in the preparation of this design and analysis report, the upgrading of the MOD-OA engineering drawings, and in performing specific design modifications and improvements on the -OA WTGs.

Several responsibilities which have been assumed by each of the utilities for the MOD-OA wind turbine project were delineated above in Section 1.2.2, Site Selection. In addition, NASA LeRC, with assistance from Westinghouse personnel, assumed the responsibility for the training of utility personnel in the operation and maintenance of the MOD-OA WTG. This included discussions and presentations on the description of the MOD-OA WTG and its performance characteristics; the automatic and manual control systems; the engineering data system, supervisory control, and network interface switchgear; the startup, operation, and shutdown of the WTG; routine maintenance requirements; and the safety design features, component operating ranges and limits, and operation hazards. An operation and maintenance manual and an initial startup and operation procedure were developed and discussed. Following the acceptance testing for each wind turbine, the participating utility company is responsible for performing the routine maintenance operations and for operating and monitoring the performance of each wind turbine for a 2 year period.

2.0 SYSTEM DESCRIPTION

The MOD-OA Wind Turbine Generator is a device for generating electrical power from wind energy. The output from the WTG is 480 V, 60 Hz, three phase current. The basic components include a rotor, a mechanical power transmission (drive) train, a generator, a yaw system, and tower for supporting the equipment. The rotor blades are located downwind of the tower to provide maximum safety from blades striking the tower. Two blades are attached to the rotor hub which turns at 40 rpm. The mechanical power train between the hub and generator includes a gear box that permits the generator to turn at 1800 rpm. All of this mechanical and electrical equipment is housed in a fiberglass nacelle supported 100 feet (30.5 m) above ground level by a four-legged truss-type structural tower. A hoist provides access to the equipment mounted on top of the tower. Onsite controls and electrical switchgear are housed in the control building at the base of the tower.

For clarity in this report, the equipment of the WTG is subdivided into various functional systems that are described separately in Section 2.3 through 2.11. The descriptions are intended to be rather brief and mostly qualitative since the design and analysis of each system is discusssed thoroughly in Section 4.0. Sections 2.1, 2.2, 2.12, 2.13 and 2.14 deal with the overall wind turbine generator rather than any individual component or system.

2.1 FEATURES AND CHARACTERISTICS

The rated power output of the wind turbine is 200 kW. This power is achieved at a turbine rotor speed of 40 rpm and a rated wind speed of 18.3 mph (8.2 m/s) at a 30 foot (9.1 m) elevation. The rated wind speed is the lowest wind speed at which full power is achieved. Power output is constant at higher winds up to the cut-out wind speed of 34.2 mph (15.3 m/s). The rotor blades have pitch control, and are placed in a feathered (no power) position whenever wind speed is not in the range of 6.9 to 34.2 mph (3.1 to 15.3 m/s). Wind speed is measured at an elevation of 30 feet (9.1 m) above grade. Directional alignment with the wind is provided by a yaw system that turns the nacelle on a turntable bearing located at the top of the tower.

Features and Characteristics

Number of Blades	2
Diameter	125 feet (38.1 m)
Speed	40 rpm
Direction of Rotation	CCW (looking upwind)
Type of Hub	Rigid
Power Regulation Method	Variable Pitch
Cone Angle of Blades	7 degrees
Tilt Angle of Axis	0 degrees
Blade Length	59.9 feet (18.3 m)
Blade Material	Aluminum
Speed of Rotor & Generator . . .	40 & 1800 rpm

Weight of Rotor with Blades	12,300 lbs. (5,580 kg)
Weight of Hardware above Tower	45,000 lbs. (20,400 kg)
Weight of Tower	44,000 lbs. (20,000 kg)
Weight, Total	89,000 lbs. (40,400 kg)

2.2 CONFIGURATION

The 200 kilowatt wind turbine consists of a rotor with blades, nacelle with internal equipment, tower, hoist, and control building. The two propeller type rotor blades rotate about a horizontal axis and are located downwind from the tower. The blades are swept downwind at a seven degree angle to provide clearance from the tower.

A cable supported hoist is located within the periphery of the tower and provides transport capability between ground level and the top of the tower. A control building is located inside the tower near one leg of the tower. Figure 2.2-1 describes the configuration.

2.3 NACELLE ARRANGEMENT

The nacelle arrangement of equipment is shown in Figure 2.3-1. All of the rotating equipment for the WTG is located inside a fiberglass nacelle and supported on a large structural bedplate. The nose cone and cylindrical sections of the nacelle are also supported on the bedplate through flange attachments. The rear or prop cone section of the nacelle rotates with the blades and therefore is supported on the rotor hub.

Support for the bedplate is provided by a large diameter gear-bearing assembly, the main support cone, and a mounting frame. The mounting frame interfaces with the tower structure which provides support for the entire nacelle arrangement in the elevated position.

2.4 ROTOR

The rotor has two all-metal blades. Each blade is 59.9 feet (18.3 m) long and weighs 2350 pounds (1066 kg). The blades were designed for pitch control and they were originally designed to produce 100 kW at 40 rpm in an 18 mph (8 m/s) wind at 100 ft. (30.5 m). Each blade has a nonlinear twist of 33.8 degrees and was fabricated by the Lockheed Company to have an NACA 23000 airfoil contour.

The rotor blades are attached to a hub on the low speed shaft. The hub is of the rigid type and houses some of the parts of the mechanism needed for changing the pitch of the blades. Wind loads, both steady and gusting, centrifugal loads and gravity loads are absorbed by the hub and transmitted to the low speed shaft. Dynamic loads resulting from yaw motion of the machine are carried in a similar manner. Inplane bending moments developed by the rotor blades are transmitted as torque loads to the shaft. All other blade loads are transmitted through the low speed shaft and bearings into the bedplate.

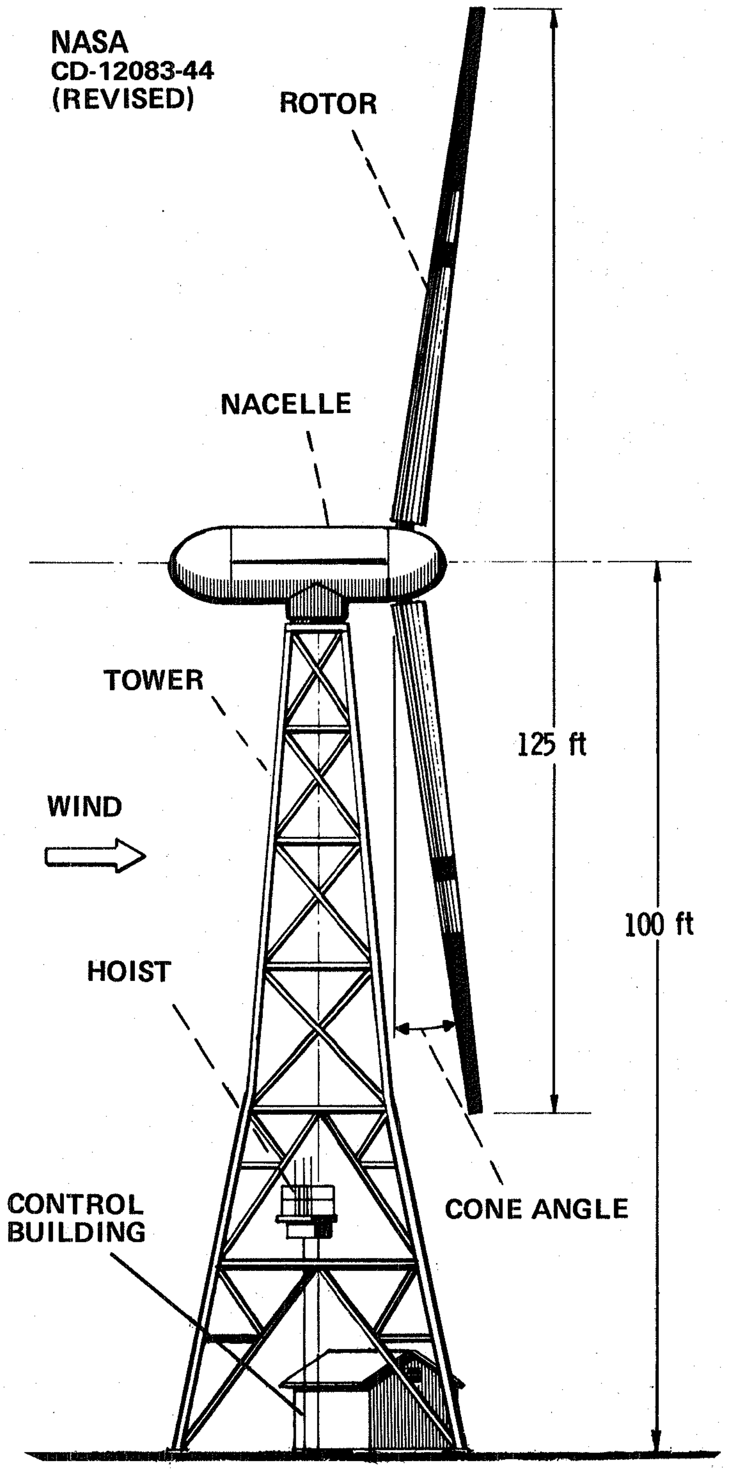

Figure 2.2-1. 200 Kilowatt Wind Turbine

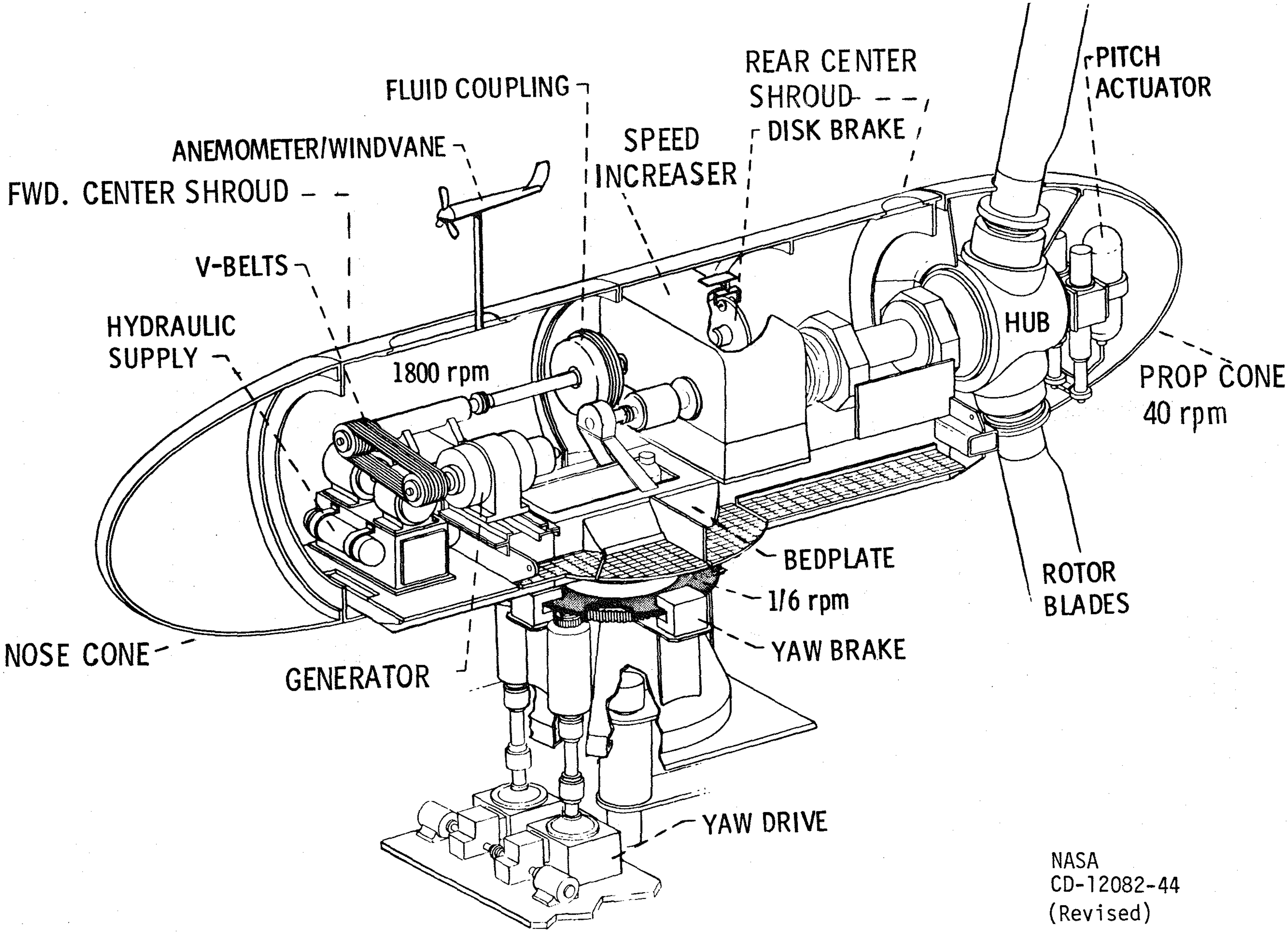

Figure 2.3-1. Nacelle Arrangement for MOD-0A Wind Turbine Generator

2.5 PITCH CHANGE MECHANISM

The pitch change mechanism consists of a hydraulic pump, a pressure control valve, rack and pinion actuators and gears to rotate the blades in the hub. The type of pitch change mechanism is similar to that used in the aircraft industry on some early propellers and is shown in Figure 2.5-1. For changing the pitch of the blades a rack-and-pinion type actuator turns a master gear which in turn rotates the blades through bevel gears attached to the spindles of the blades. The hydraulic pump is mounted separately on the structure enclosed by the nose cone. Hydraulic fluid is brought into the shaft by a rotating hydraulic union. The maximum rate of pitch change is eight degrees per second.

The pitch change mechanism operates in conjunction with the pitch hydraulic system for the purpose of controlling either rotor speed or rotor power. This action of the mechanism is accomplished by changing the pitch angle of the rotor blades while the blades are rotating about the horizontal axis of the WTG. For the MOD-OA machines, rotor speed is held constant at 40 rpm during normal operation and blade pitch is changed to produce rated power (200 kW). When wind speed is too slow or too fast to operate the WTG, the mechanism keeps the blades feathered to reduce torque on the rotor. The various motions of the mechanism are controlled by the pitch control system.

2.6 PITCH HYDRAULIC SYSTEM

The pitch change mechanism described in Section 2.5 is activated by the Pitch Hydraulic System. Hardware for this system is located partly on the downwind side of the rotor hub and partly within the nose cone. The principal elements of the system along with interconnecting piping are shown in the simplified schematic diagram of Figure 2.6-1.

The mechanism drive gear is engaged with a gear rack on either side. The motion of each rack is determined by the motion of a hydraulic actuator connected to each rack. As shown in the diagram, the direction of motion of the actuators is determined by the position of the control valve. When this electrohydraulic servo-valve is in the position shown, hydaulic fluid flows from the pump through the lower part of the valve, into the left end of the upper actuator and into the right end of the lower actuator. This produces movement of the gear racks, thus turning the mechanism drive gear and changing the pitch of the rotor blades through the action of the Pitch Change Mechanism. Opposite motion is achieved by changing the position of the control valve.

2.7 YAW MECHANISM AND BRAKE

The nacelle of the WTG and all of the equipment housed in the nacelle are supported on a large diameter turntable bearing which permits angular turning about a vertical axis to maintain proper alignment with the wind. This yawing action is achieved by two pinion gears which drive a large bull gear machined into the circumference of the turntable bearing and bolted to the bedplate of the WTG. The pinion gears are preloaded against each other to eliminate backlash and produce a stiff system. Separate motors and gear boxes drive each

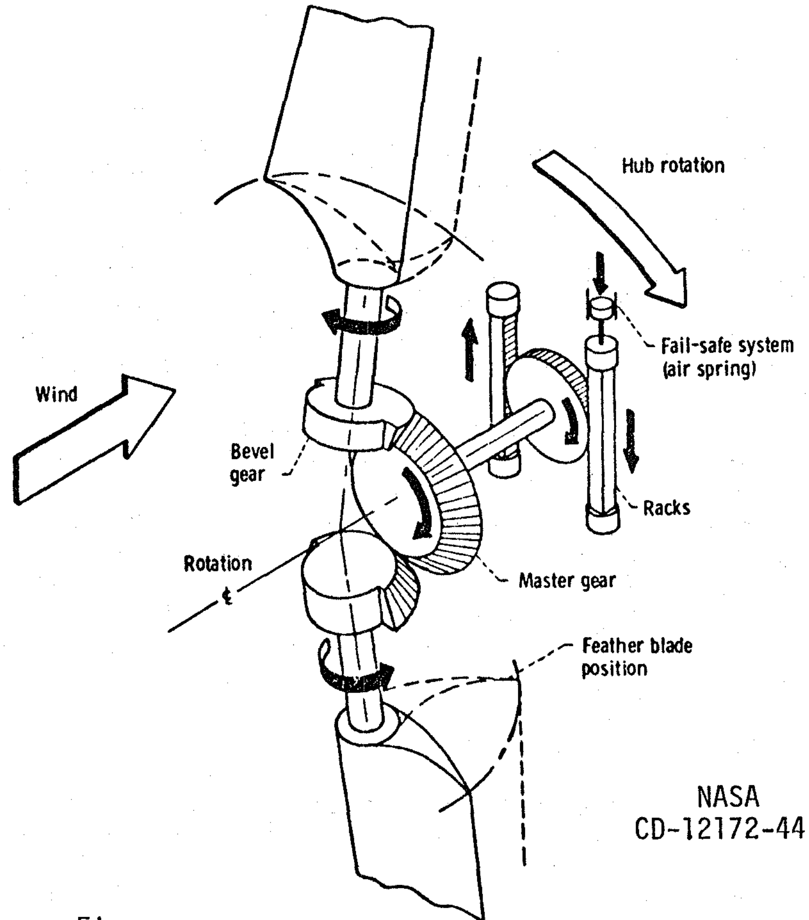

Figure 2.5-1. Blade Pitch Change Mechanism

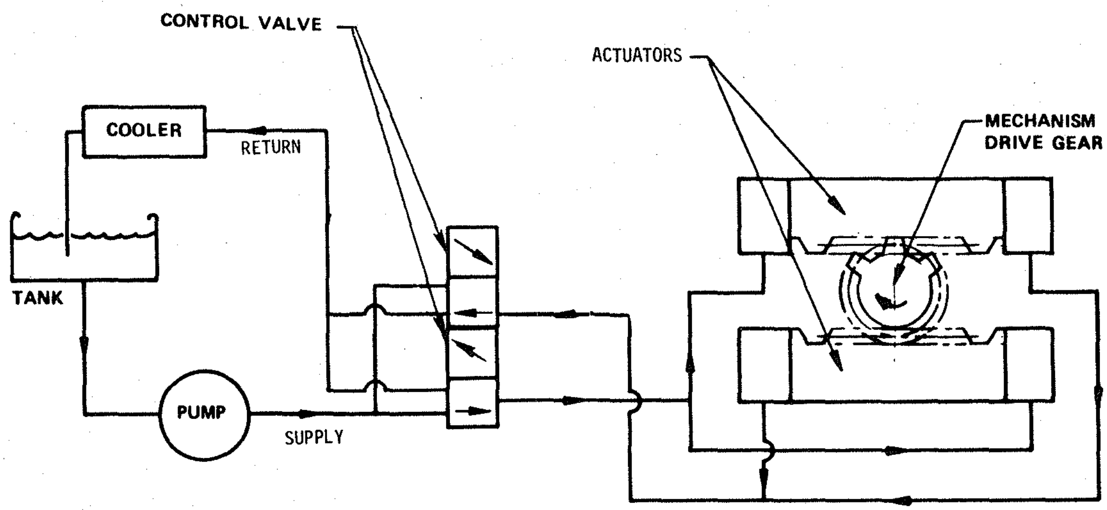

Figure 2.6-1. Pitch Hydraulic System Schematic (Simplified)

pinion gear. The motor shafts are coupled together to maintain the preload and give redundancy to maintain yaw control even if one motor fails. The yaw system is operational whenever the wind speed exceeds the cut-in wind speed of 6.9 mph (3.1 m/s) at a 30 foot (9.1 m) elevation. Figure 2.7-1 describes the basic features of the yaw drive system.

The yaw brake system consists of three large disc brakes that are bolted to brackets on the yaw cone structure. When activated, each brake grips a large diameter disc-ring that is bolted to the turning race of the turntable bearing. This gripping action prevents the nacelle and its internal equipment from turning, in yaw. A second function of the brake system is to provide controlled damping when the yaw system is orienting the machine for a change in wind direction. This action also serves to add stiffness to the yaw system and reduce any tendency for the yaw motions to be jerky. Figure 2.7-2 depicts the yaw brake system. The yaw mechanism and brake are described in Section 4.4.

2.8 TOWER AND FOUNDATION

The tower for supporting the nacelle, the blades, and the equipment housed in the nacelle has a square base of 30 feet (9.1 m), a cap span of 7 feet (2.1 m), and is approximately 93 feet (28.3 m) tall. It must withstand high winds and rotor thrust loads, both steady and cyclic, during operation of the machine.

The structure of the tower is designed to minimize the wind shadow created by the tower. This is achieved by using tubular members that are arranged to form an open truss-type structure and thereby reduce cyclic stresses on the blades as they pass through the wake of the tower. Access to the top of the tower is provided by a cable mounted hoist. The hoist was selected over conventional stairs in order to maximize air flow through the tower.

The foundation for supporting the tower consists of a large reinforced concrete slab containing 170 cubic yards (130 m^3) of concrete. The tower is securely anchored to the slab that is buried below grade in order to prevent being overturned by high winds.

2.9 ELECTRICAL POWER SYSTEM

The MOD-OA wind turbine electrical power system must produce power at a voltage and frequency compatible with the interfacing utility network, protect both the wind turbine and the utility with standard devices and practices, and provide for unattended operation to synchronize and automatically disconnect the systems as required. The power generation requirement imposed on the MOD-OA design is 200 kW at a rated wind speed of 22.4 mph (10 m/s) (hub height).

A simplified one-line diagram of the MOD-OA wind turbine power distribution system is illustrated in Figure 2.9-1 and the complete one-line diagram is presented in Figure 4.6.2-1. The electrical power necessary to start the wind turbine is not provided as part of the wind turbine. The utility network must provide the power to initiate operation.

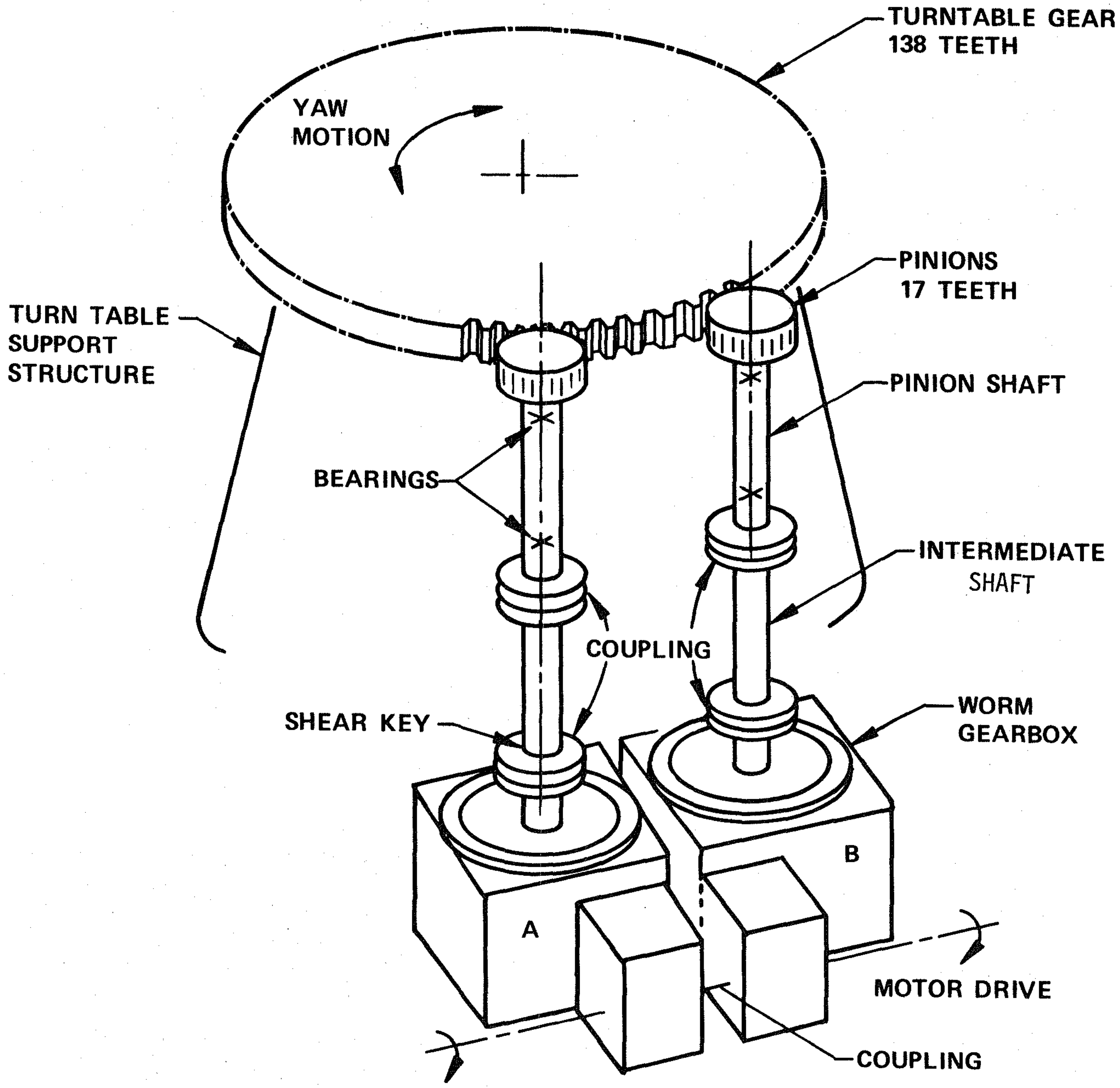

Figure 2.7-1. Yaw Drive System

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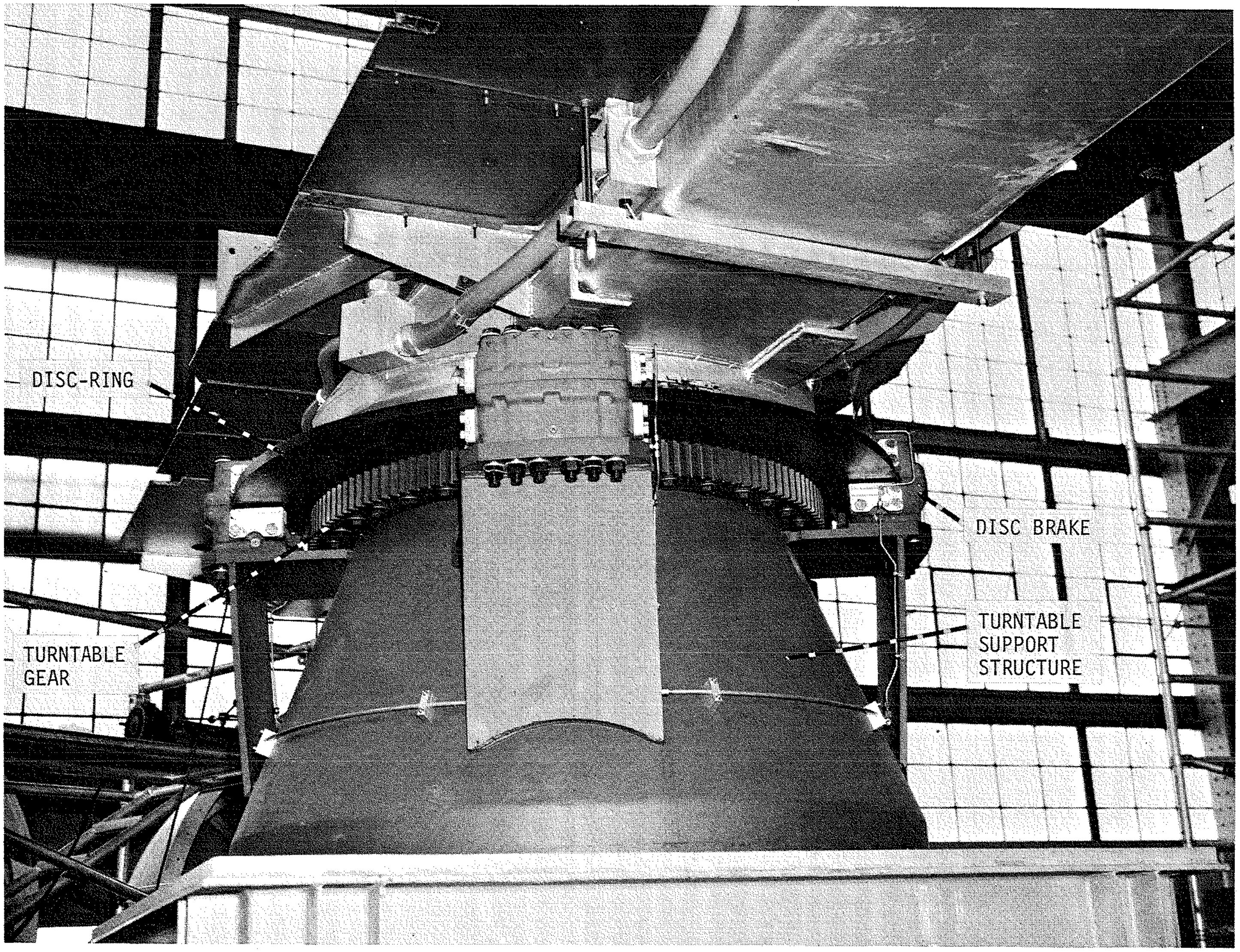

Figure 2.7-2. Yaw Brake System

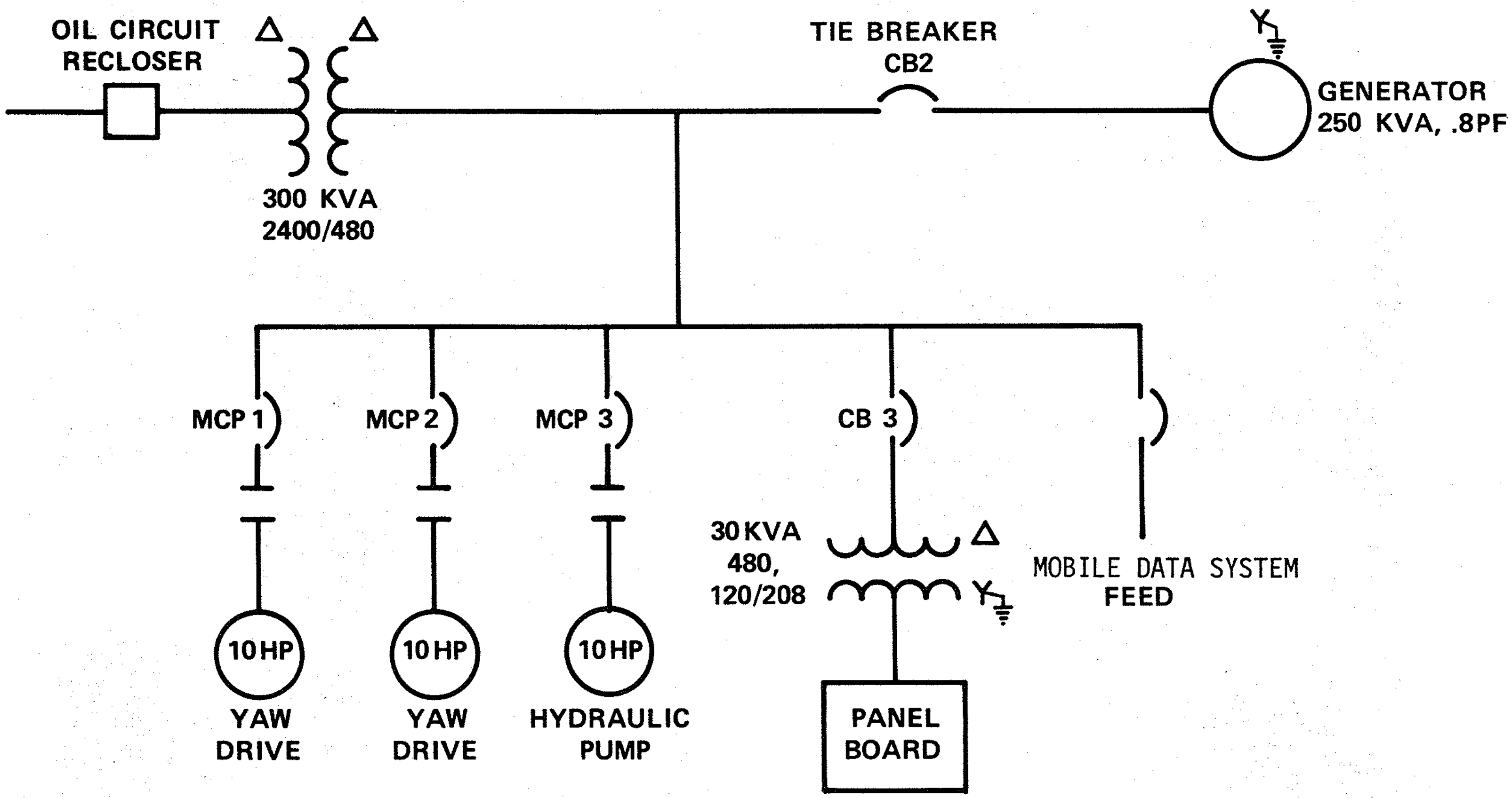

Figure 2.9-1. Simplified One-Line Diagram of the Electrical Power Distribution System

The electrical power system for the MOD-OA wind turbine consists of the generator, the generator controller, the utility interface switchgear and associated protective equipment. The MOD-OA generator is a 250 kVA, .8 power factor synchronous machine with a rated output voltage of 480 V, three phase, four wire, 60 Hz and a rated input of 1800 rpm. The exciter is a brushless type which is directly connected to the generator.

The voltage regulator associated with the generator is of solid state construction and provides for operation in the manual and automatic modes. In the automatic mode the regulator senses the output of the generator and regulates the voltage to be compatible with the interfacing utility. In the manual mode the regulator can adjust the generator field excitation from zero to rated value. A VAR controller is used in conjunction with the voltage regulator to control the reactive load current of the generating system. Normal MOD-OA operation is VAR control.

Electric power is transmitted from the generator, through slip rings to a cable, to the base of the tower. At the tower base the cable is run to the switchgear in the control building, through the tie breaker, through a step-up transformer and to the utility network through an oil circuit recloser. The transformer is an outdoor, oil insulated, self-cooled, padmounted, 2400/480 V, 300 kVA transformer. The oil circuit recloser is rated at 14.4 kV, 560 A. The transformer and recloser are located at ground level adjacent to the control building.

Synchronization of the wind turbine with the utility network is accomplished with an automatic synchronizer. The synchronizer monitors the phase angle between and the frequencies of the systems and provides a corrective signal to the wind turbine speed controller to match the wind turbine output with that of the utility network. When both systems are within specification ±5° for 0.75 seconds, the synchronizer provides the intelligence to close the tie breaker and mate the wind turbine with the utility.

The electrical system is protected against electrical faults with standard electromechanical relays. The design provides protection in the form of overcurrent voltage restraint, reverse power, instantaneous and time overcurrent relays on the phase conductors as well as a time overcurrent relay in the generator neutral.

As a part of the switchgear, located within the control building, provisions are made to supply the ancillary load requirements of the wind turbine. Motor circuits are included to provide 480 V to two yaw drive motors and the hydraulic pump motor. A 480 V feed is provided for the data van and a stepdown transformer and associated panelboard are included in the design to service the 120/208 V loads.

2.10 CONTROL SYSTEMS

The MOD-OA wind turbine was designed to be a fully automatic power generator tied to a utility network. To achieve this objective, the wind turbine control

system is capable of monitoring wind conditions, maintaining nacelle alignment with the wind, controlling rotor speed and power level, and starting, synchronizing, and stopping the wind turbine in a safe manner. In addition, the control system must monitor essential parameters throughout the wind turbine to assure that critical components are operating within specified tolerances. The control system also provides a remotely located operator with the capability of starting, stopping, and monitoring the wind turbine.

The control system to accomplish the majority of the control functions can be divided into five distinct control systems. These five control systems consist of rotor blade pitch control, yaw control, microprocessor control, the safety system, and the remote control and monitoring system. A block diagram depicting the interactions of the control systems is shown in Figure 2.10-1. The five systems operate nearly independently and are interfaced through the microprocessor.

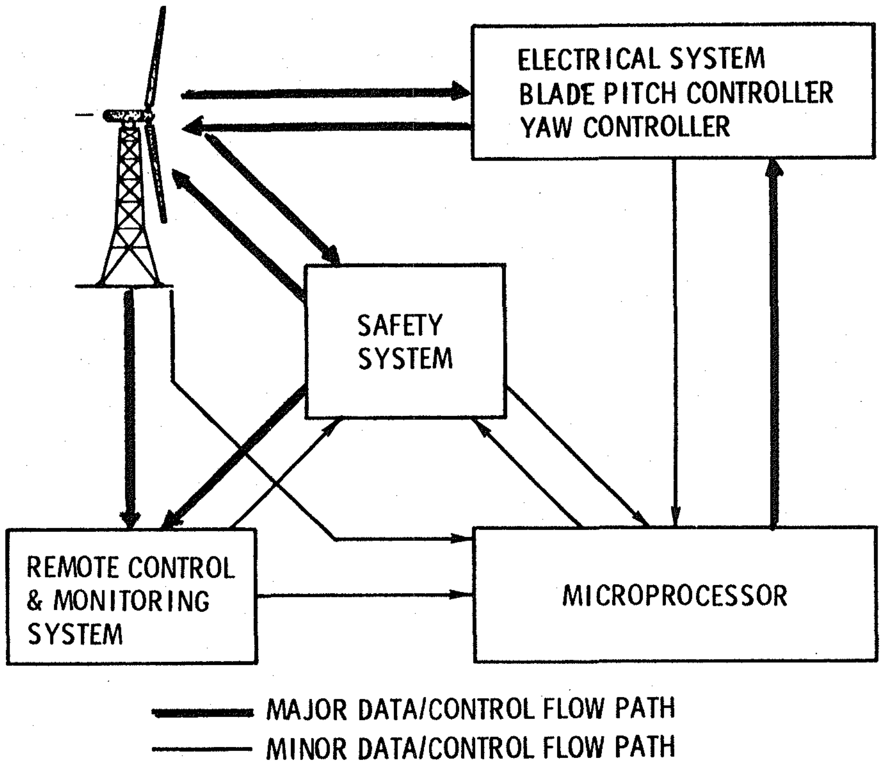

Figure 2.10-1. Control System Interfaces

Wind turbine rotor power is a function of wind speed and blade pitch angle. As a result, either rotor speed or rotor power at a given rotor speed can be controlled by adjusting blade pitch angle. The blade pitch controller for the MOD-0A machine operates in three distinct modes. Position control is used during initial rotor startup and shutdown. Speed control is used in the intermediate phase of startup between 5 rpm and 40 rpm until the machine is synchronized with the utility network. Closed loop power control is utilized

whenever the machine is synchronized with the utility network. The blade pitch angle is driven toward zero degrees when the wind speed is below that required to produce 200 kW of power. The pitch angle is varied to spill wind when the wind speed is in excess of that required to maintain a 200 kW power level. To shut the machine down, the blade pitch angle is reduced at a uniform rate until the blades are feathered. The blades remain feathered until a command to start up the WTG is received.

The yaw controller senses directional error from the anemometer/wind vane mounted on the nacelle which monitors wind direction relative to the nacelle, providing a direct measure of the yaw error. The yaw controller has a $\pm 25°$ deadband which must be exceeded prior to initiating a correction. The yaw drive system rotates the nacelle at a rate of 1° per second. A yaw brake is used to provide nacelle restraint in yaw, both when the yaw motors are on and when they are off. During yaw maneuvers, the brake pressure is reduced. When no yawing is required, the brake pressure is increased and the nacelle is essentially locked to the tower.

The microprocessor is the control unit which permits unattended, automatic operation of the wind turbine. The unit provides the commands to initiate startup, control normal operation, and shutdown the wind turbine, based on wind conditions. Once the microprocessor has been activated, no other function is required of an operator, unless he wants to shut down the machine and/or disable the microprocessor.

Once the microprocessor is activated, it monitors the wind and initiates a startup sequence when the wind speed exceeds 12 mph (5.4 m/s) at hub height. Once synchronized, the machine continues to operate until a wind speed below 8 mph (3.6 m/s) or above 40 mph (17.9 m/s) (hub height) is reached. If either of these conditions exist, the microprocessor initiates a shutdown and waits until the wind speed is within the acceptable range before restarting the machine.

The microprocessor is also programmed to shut down the wind turbine whenever certain abnormalities are detected. The abnormalities include slow startup or synchronization, loss of pitch hydraulic pressure, and loss of synchronization. Each of these abnormalities initiates a shutdown and requires on-site resetting prior to resumption of normal operations.

Unattended operation dictates that a separate independent protective system monitor the wind turbine and effect a safe shutdown if a malfunction or out of tolerance performance is detected. The shutdown system is functionally independent of other control systems and includes a series of primary sensors connected to an interface/annunciator circuit. The annunciator provides an indication of the cause of the shutdown. The output of the interface circuitry controls a relay logic system which effects a safety shutdown by feathering the rotor blades and desynchronizing the generator. The safety system includes a primary and a redundant set of sensors. The redundant sensors operate through an independent path to effect the shutdown and provide a backup to insure safety in the event of a failure in the primary system.

The remote control and monitoring system provides an interface between the wind turbine and a remote operator. The system serves as a control link, status

indicator, and performance monitor. The interconnection between the wind turbine and the remote unit is effected by two telephone pairs. The remote system is capable of two control functions: startup and shutdown of the wind turbine through the microprocessor and emergency shutdown through the safety system. Status indications show wind turbine operable or shutdown, microprocessor status, and error conditions from the safety system. Performance of the wind turbine can be monitored by any two of eight channels of analog data which are digitally displayed in engineering units.

2.11 INSTRUMENTATION AND DATA ACQUISITION

The instrumentation and data acquisition system collects the data required for evaluating the operation and performance of the MOD-OA wind turbine. The system consists of sensors located in the nacelle, the control building, and the meteorological tower; three remote multiplexing units; a mobile data system; and a stand alone instrument recorder.

The sensors associated with the data system are segregated according to their specific locations and discussed in Section 8.1. The outputs of the sensors provide input to three remote multiplexer units (RMU's), where the signals are multiplexed and sent to the mobile data system for processing.

The remote multiplexing units are located on the hub, on the bedplate, and in the control building. Each RMU contains the electronics required for signal conditioning and multiplexing data signals (FM technique) for transmission to the mobile data system. Each RMU can accommodate up to 32 data channels. All channels can be individually configured to signal condition data from resistance outputs or voltage sources. In addition, 20 of the 32 channels have the capability to signal condition inputs from type "T" copper/constantan thermocouples.

The mobile data system provides the equipment necessary to process data at the wind turbine site. This self-propelled instrument vehicle is constructed to a) permit movement from site to site over public roadways without special permits or approvals and b) provide a controlled environment for the equipment contained within the vehicle. An overview of the flow of data within the mobile data system is illustrated in Figure 2.11-1. The equipment with the mobile data system essentially collects wind turbine data and processes/records it in a usable form. Refer to Section 8.3 for further details on the mobile data system.

The stand alone instrument recorder (SAIR) recorded data when the mobile data system was not at the site. The SAIR provided for continuous, 24 hours per day, recording of four tracks of data. Three of the data tracks supported the three RMU's and the fourth track supported an internally generated time of day time code signal. The tape consisted of a continuous loop which provided a stored record of the previous thirty minutes of data.

2.12 PREDICTED PERFORMANCE

The rated power output of the wind turbine is 200 kW, which is achieved at a turbine rotor speed of 40 rpm and a rated wind speed of 18.3 mph (8.2 m/s) at a 30-foot (9.1 m) elevation [22.4 mph (10.0 m/s) at a 100-foot (30.5 m) ele-

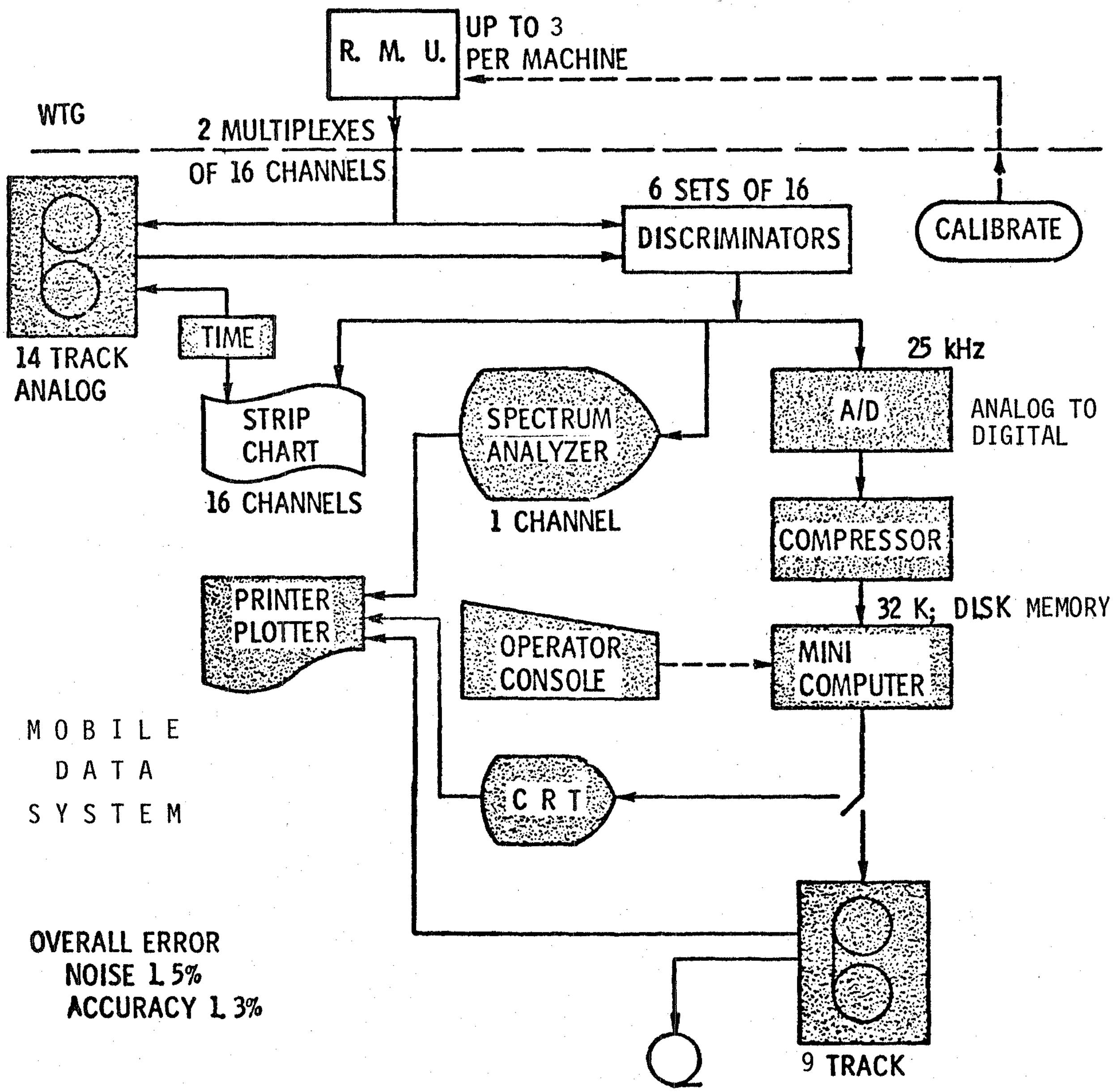

Figure 2.11-1. Mobile Data System Overview

vation].[22] The rated wind speed is defined as the lowest wind speed at which full power is achieved. The power output as a function of wind speed, as shown in Figure 2.12-1, is regulated by varying the pitch angle of the blades.

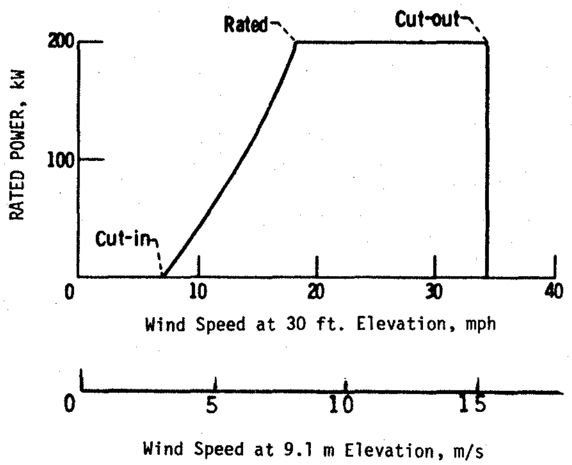

Figure 2.12-1. Power Output as a Function of Wind Speed

The relationship between rotor power and blade pitch angle is given in Figure 2.12-2. At wind speeds below cut-in and above cut-out, the rotor blades are placed in a feathered position and no power is produced. The cut-in wind speed, defined as the lowest wind speed at which power can be generated, is 6.9 mph (3.10 m/s) at a 30-ft (9.1 m) elevation [9.6 mph (4.30 m/s) at 100 ft (30.5 m)]. The cut-out wind speed, defined as the lowest wind speed at which wind turbine operation would result in excessive blade loads, is 34.2 mph (15.3 m/s) at a 30-ft (9.1 m) elevation [40.0 mph (17.9 m/s) at 100 ft (30.5 m)].

The calculated annual energy output for the 200 kW wind turbine operating in various average wind speed environments is shown in Figure 2.12-3. The average wind speed is the arithmetic average of all hourly wind speeds in a given year at that particular site measured 30 feet (9.1 m) above ground level. The energy output is a strong function of the average wind speed, since the available energy in the wind is proportional to the cube of the wind speed. The energy output was computed using the power output shown in Figure 2.12-1. Velocity profile curves for the wind were assumed to be Weibull distributed. Energy capture by the rotor was computed using the wind speed occurring at the hub height of 100 feet (30.5 m). Wind speeds at various elevations were calculated by using the wind shear gradient typical of most of the candidate wind turbine sites. It was estimated that the machine would be shut down ten percent of the time when the wind velocity was between cut-in and cut-out speeds. This shutdown time was allowed for both scheduled and unscheduled maintenance.

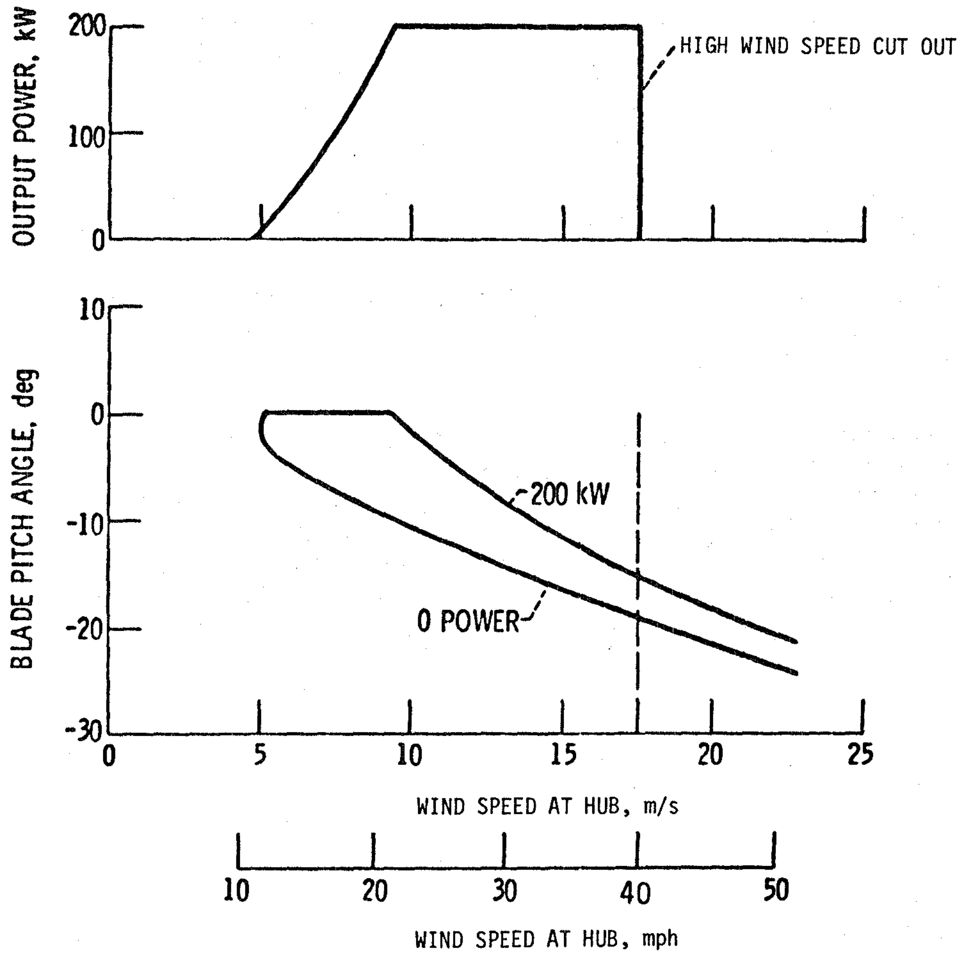

Figure 2.12-2. MOD-0A 200 kW Wind Turbine Power Control-Output Power and Blade Pitch Angle Versus Wind Speed

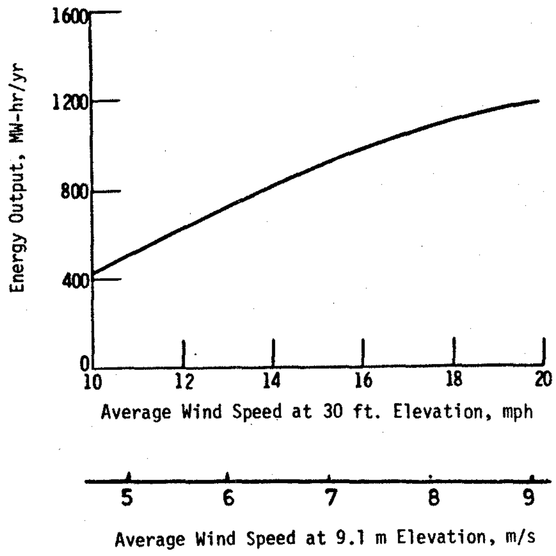

Figure 2.12-3, Annual Energy Output for 200 kW Wind Turbine

2.13 COST

The total cost of the Clayton MOD-OA wind turbine (in 1978 dollars) was \$1.7 million. A breakdown of the costs is given in Table 2.13-1. The blades were manufactured by the Lockheed Aircraft Service Co., Ontario, CA, under a NASA contract. NASA LeRC managed the procurement of the long lead parts. The assembly and in plant testing was conducted by NASA at the LeRC. Site installation and some of the startup operations were performed by the Westinghouse Electric Corporation under a NASA cotract.

TABLE 2.13-1

MOD-OA 200 kW WTG Costs (\$K)

(1978 Dollars - Clayton, NM)	
Blades (2)	450
Hub and Pitch Change	160
Mechanical Equipment	230
Electrical Equipment	110
Control Systems	40
Tower and Hoist	140
Shipping	40
Installation	200
Startup Operations	150
Engineering Data System	180
Total cost	\$1700K

2.14 WEIGHT SUMMARY

The total system weight is 89,000 pounds (40,400 kg). The rotor, including blades, weighs 12,300 pounds (5,580 kg). Above the tower weight is 45,000 pounds (20,400 kg), while the tower weight is 44,000 pounds (20,000 kg). A detailed system weight breakdown is given in Table 2.14-1.

TABLE 2.14-1

MOD-OA 200 kW WTG Weights

COMPONENTS OR SYSTEM	LBS	KG
Blades (2)	4,700	2,100
Hub	6,660	3,020
Pitch change mechanism	2,440	1,100
Speed Increaser	5,500	2,500
Generator	2,270	1,030
Yaw bearing, drive and brake system	3,900	1,770
Nacelle	4,000	1,800
Support Cone	2,280	1,030
Bedplate	8,310	3,770
Miscellaneous	4,940	2,300
Above the Tower (Total)	45,000	20,400
Tower	44,000	20,000
Total	89,000	40,400

Further details on the weights of some of the components and systems are provided in Table 3.2-1 and Section 4.0.

3.0 SYSTEM DESIGN REQUIREMENTS AND SPECIFICATIONS

The design requirements for the MOD-OA WTG system are presented in Section 3.1. These overall requirements are defined as the system objectives, criteria, and constraints that needed to be considered and satisfied during the development of the wind turbine design. The system design requirements have been subdivided into a number of different categories. In addition to these overall design requirements, further details on the specific requirements for the design of discrete components and systems are delineated in their respective subsections of Section 4.0, Design and Analysis, and Section 8.0, Engineering Data Acquisition. Section 3.2, System Specifications, summarizes the system specifications that were developed to satisfy the design requirements. Also, detailed specifications, as they relate to a specific system or component, are discussed in depth in Sections 4.0 and 8.0.

3.1 SYSTEM DESIGN REQUIREMENTS

The MOD-OA WTG was a first-generation wind urbine that, like the MOD-0 100 kW WTG, was analyzed, designed, and built on an accelerated schedule by the NASA LeRC. At the beginning of the project, several of the system design requirements were not well understood and/or documented. These design requirements were developed and continuously revised during the MOD-OA project as new information was learned, particularly from the design, assembly, and operation of the MOD-0 machine. The requirements delineated in this section represent a compilation of the system design requirements. These include those that were specified/considered at the initiation of the project, as well as those that were developed (or upgraded) during the course of the project.

The overall system design requirements for the MOD-OA WTG have been subdivided as they apply to the following specific categories: General, Mechanical Components and Systems, Electrical Components and Systems, Control Systems, Engineering Data Acquisition, Environmental, and Safety and Failure Modes and Effects Analysis. Obviously, some of the design requirements discussed under the General, Environmental, and the Safety and Failure Modes and Effects Analysis areas are applicable to more than one of the other categories. With regard to the mechanical and electrical components and systems, the control systems, and the engineering data acquisition system, significantly greater detail on the specific requirements for the design of those components and systems are given in their respective subsections of Section 4.0, Design and Analysis, and 8.0, Engineering Data Acquisition. Each of the above mentioned categories of system design requirements are discussed in the pages which follow.

GENERAL

The general system design requirements for the MOD-OA WTG were as follows:

- Develop an experimental intermediate-size horizontal-axis WTG that is an uprated version of the MOD-0 wind turbine, by increasing the power rating of the MOD-0 WTG without changing major developmental power components significantly.

- Based on these uprating requirements, the rated electrical power output of the WTG was selected to be 200 kW.

- The high cut-out wind speed (the wind speed above which the machine is shut down and the blades are feathered) was selected to be 40 mph (17.9 m/s) at hub height.

- Provide fail-safe shutdown capabilities.

- All static components of the MOD-OA WTG, e.g., the tower, foundation, and bedplate, must be designed for a 50-year life. All dynamic components, with the exception of the blades, are to be designed for a 30-year life. The blades are to be designed to withstand the loads measured on the MOD-0 machine.

- Design the WTG for operation in conjunction with existing utility networks, including operation in parallel with diesel or other electrical power generating equipment.

- Provide a design of the MOD-OA WTG which meets all of the applicable design codes and standards, e.g., ASME, The American Institute of Steel Construction (AISC), American Concrete Institute, National Electrical Code, and IEEE and NEMA Standards, and which satisfies the applicable OSHA requirements during the assembly, testing, construction, and operation of the WTG.

- Develop a reliable, moderate-cost WTG that is straightforward and conservative in design, and requires only minimal maintenance in service.

- Provide a design of the MOD-OA WTG that permits flexibility in the selection of the rotor speed, and develop the criteria for that final selection. The development of this criteria must take into account and evaluate the following considerations: a) the need to maintain a reasonable blade tip speed for blade design purposes, b) the need to keep the centrifugal forces and the dynamic blade loads and bending moments, which result from the dynamic interactions of the blades with the tower shadow, wind shear, wind gusts, yawing motion, Coriolis, coning, and blade pitching effects, within acceptable limits,

and c) the need to select a moderate tip speed-to-wind speed ratio (i.e., in the range typically between a value of four and eight, so as to yield a relatively high value of the power coefficient, approaching the theoretical maximum Betz coefficient, for a high-speed two-bladed horizontal-axis WTG[1]). On this basis, the baseline design for rotor speed of the -OA WTG was selected to be 40 rpm.

More recently, one of the design requirements for wind turbines is the stipulation of a mean wind speed for the site so that the design can be optimized for minimum cost of energy and/or maximum energy production. As mentioned above in Section 1.2.1, the MOD-OA WTG was not optimized for maximum energy production. Thus, the MOD-OA design was to be developed considering that the wind turbine would be located at sites with a mean annual wind speed in the range of 14-18 mph (6.2-8.0 m/s) at hub height [the Clayton MOD-OA WTG should encounter a mean annual wind speed at a 100 foot (30.5 m) elevation of approximately 15 mph (6.7 m/s)]. However, this did not represent a design requirement for the MOD-OA WTG.

MECHANICAL COMPONENTS AND SYSTEMS

Many mechanical components and systems were incorporated into the MOD-OA design. These include the rotor (blades, hub, pitch change mechanism, and pitch hydraulic system); low speed shaft, low speed bearings, and coupling; speed increaser (transmission or gearbox); high speed shaft, rotor brake, high speed shaft bearings, and couplings: fluid coupling; belt drive; nacelle equipment (bedplate, nacelle, turntable bearing and gear assembly, support cone, and mounting frame); yaw (orientation) drive mechanism and yaw brake; tower; foundation; service stand; and the equipment and personnel hoist. The mechanical design and associated analyses for each of these components and systems of the WTG were performed to satisfy several mechanical system design requirements. In addition to the requirements discussed below, further details on the specific design requirements for the various systems and components are treated in their respective subsections of Section 4.0, Design and Analysis. The overall mechanical design requirements were as follows:

- As discussed above under Section 1.0, Project Requirements and Approach, the MOD-OA WTG design was to be developed and based on the MOD-0 wind turbine configuration. Therefore, the -OA WTG was to have a horizontal-axis, 125 foot (38.1 m) diameter rotor with a rigid hub that rotates at 40 rpm and supports two blades located downwind of the tower and cantilevered downwind at a 7° cone angle. Further details on the specific design requirements for the rotor (blades and hub) and pitch change mechanism are given in Section 4.1.

- Develop and utilize specific requirements with respect to the definition of the wind regime and wind environment, e.g., wind gust criteria and vertical wind profile (wind shear), including tower shadow effects.

- Develop and utilize specific requirements concerning the steady and cyclic loads on the WTG, and especially of the loads on the rotor (four separate blade load cases are discussed in detail in Section 4.1.1). The dynamic blade loadings shall include aerodynamic, gravitational and inertial effects.

- In addition to the blades, the balance of the rotor design, which includes the hub, low speed shaft, and bearings, must be designed to handle the static and dynamic loads which result from the wind environment, wind gusts, tower shadow, and wind shear.

- Design a pitch change mechanism and a pitch hydraulic system for the blades to a) maintain the blade pitch angle at 0° when the wind speed is above the cut-in wind speed and below that required to produce 200 kW of electrical power, b) decrease and then vary the pitch angle to spill wind when the wind speed is between the rated wind speed and the cut-out wind speed, so as to maintain an electrical power output of 200 kW, and c) reduce the blade pitch angle at a uniform rate until the blades are feathered, so as to shut down the WTG. The pitch change mechanism and its associated hydraulic system must be designed to control the rotating speed of the WTG under all operating wind conditions and to protect the rotor and blades from overspeed in a fail-safe manner.

- Additional requirements for the design of the pitch change mechanism and hydraulic system, as they relate to blade weight, maximum torque, various pitching rates (including an emergency feather condition), and a backup means to feather the blades in the event of a hydraulic system failure, are discussed in Section 4.1.3. Also included is the development of an operating performance envelope of blade pitch angle as a function of wind speed within which the WTG must be controlled to operate.

- The low speed shaft and couplings must be designed to transmit the torque generated by the wind turbine blades (through the rotor hub) to the input shaft of the speed increaser (gearbox). The low speed shaft, bearings, and couplings must also provide complete support for the rotor hub and blades. Specific details on the maximum critical loads for the low speed shaft, including loads during yawing and considering fatigue, are discussed in Section 4.2.1. The bending moment for the two large bearings which support the low speed shaft is also a specific design requirement.

- A flexible coupling must be designed or selected which can connect the upwind end of the low speed shaft to the input shaft of the speed increaser. This coupling transfers the

torque into the speed increaser, even though there may be lateral or angular misalignment; and must be capable of absorbing impacts due to fluctuations in shaft torque that might be induced by wind gusts.

- A speed increaser must be designed or selected to convert the wind power from the blades and the low speed shaft rotating at a speed of 40 rpm to the high speed shaft and the generator rotating at 1800 rpm. Thus, the speed increaser (gearbox) unit must have a speed increase ratio of 45:1. The speed increaser must have parallel input and output shafts and these shafts will be oriented in a horizontal position. During operation, the speed of the unit will be constant. During startup and shutdown operations, the speeds of rotation for the shafts are less than those during power operation. Further details on the specific design requirements for the speed increaser, including the steady state, shock, overload, and reverse loading are discussed in Section 4.2.2. Also included are the lubrication, design life, efficiency, and dimensional and configuration requirements.

- A rotor brake must be designed and incorporated into the WTG. This braking system must be capable of shutting the rotor down and bringing it to a full stop in the event of a catastrophic failure of the high speed shaft, belt drive, or generator, or other critical shutdown conditions. This rotor brake should be located on the high speed shaft as close to the speed increaser as possible. Specific requirements for the maximum torque for the disk type rotor brake, as well as the side loads by the brake acting on the shaft, are discussed in Section 4.2.2.

- The basic requirement for the high speed shaft, couplings, belt drive, and fluid coupling is that these components (rotating at 1800 rpm during normal operation) must transmit the torque from the output shaft of the speed increaser to the shaft of the generator. The fluid coupling must be designed to provide a small amount (nominally 2 percent) of slip in the drive train to damp out the torsional variations in wind power.

- Design a ring-gear type yaw drive mechanism (orientation drive) using electrical motors that is capable of rotating the nacelle into the wind, when directed by the yaw control system, at a rate of 1° per second. The yaw drive mechanism must be designed with no backlash and high stiffness.

- The yaw brake must be capable of providing damping and yaw restraint when the yaw motors are both on and off. During yaw maneuvers, a moderate pressure on the yaw brake is maintained to avoid more severe loads on the blades; when the yaw motors

are off, the brake pressure is increased so that the nacelle is essentially locked to the tower.

- Design a truss type tower and its foundation that provide a rigid support for all of the components located on the top of the tower, handle all of the static and dynamic loads that are transmitted to the tower, and provide for a hub height of 100 feet (30.5 m). The tower should be designed with pipe construction to minimize the tower shadow effects on the blades.

Additional design requirements for the mechanical components and systems are covered in the General, Environmental, and Safety and Failure Modes and Effects Analysis categories of these overall system design requirements.

ELECTRICAL COMPONENTS AND SYSTEMS

The system design requirements for the electrical components and systems (excluding the control systems and the instrumentation and data acquisition system) are discussed below. These encompass some of the requirements for the generator, slip rings (low speed shaft/bedplate and bedplate/tower), switchgear, transformer and oil circuit recloser, hydraulic pump motors (for pitch hydraulic system and yaw brake), two yaw drive motors, and the components that feed electrical power to the mobile data system and to the parasitic loads of the WTG. The overall electrical design requirements were as follows:

- Select a synchronous generator for the MOD-OA WTG that can convert the mechanical power from the wind to electrical power, in accordance with the mechanical parameters on the drive train side and the electrical parameters on the output side. The generator should rotate at 1800 rpm and be rated at 250 kVA continuous, 0.8 power factor, with a minimum efficiency of ninety percent. The electrical output of the generator must be 480 V, 3 phase, 60 Hz, grounded wye. The generator should be self-cooled, have a drip proof enclosure and class B insulation, and be capable of operating in the motoring mode for testing of the drive train.

- Select switchgear which incorporates those devices and components required to control and protect the generator, synchronize the WTG to the utility network, and provide the parasitic power requirements of the WTG.

- Provide a design which is compatible with typical utility networks and more specifically with the Clayton network. This should include operation in parallel with diesel generators and other requirements, such as voltage and frequency control of generated power.

- Provide a design which protects both the wind turbine and the utility with standard devices and practices.

- Provide a design which supplies the electrical power necessary to start up the wind turbine. This power must be supplied by the utility network. Thus, the switchgear design must provide for the parasitic load requirements of the WTG, that is the electrical power for the two yaw drive motors and the hydraulic pump motor, and power to feed the mobile data system and other parasitic loads of the WTG.

- Provide protection against electrical faults; more specifically, provide protection in the form of overcurrent voltage restraint, reverse power, and instantaneous and time overcurrent relays on the phase conductors.

Detailed design requirements for each of the electrical components and systems, including the requirements for the other electrical components not discussed above, are covered in their respective subsections of Section 4.0, Design and Analysis.

CONTROL SYSTEMS

Several control systems were incorporated into the MOD-OA design. These systems were the blade pitch control, generator control, yaw control, safety system, manual control, automatic control, and the remote control and monitoring system. Major components of most of these systems are maintained within a control building. The electrical design and associated analyses of these components and systems were performed to satisfy a set of control system design requirements. In addition to the requirements discussed below, further details on the specific design requirements for these systems and their components are treated in their respective subsections of Section 4.7, Control Systems. The overall control system design requirements were as follows:

- The blade pitch control system must be capable of operating in three distinct modes: position control for initial rotor startup and shutdown, speed control for the intermediate phase of startup between 5 rpm and 40 rpm, and closed loop power control with wind feed forward compensation when the machine is synchronized to the utility network.

- The yaw control system must be capable of sensing the directional error between the nacelle and its wind vane and effect a correction if a $\pm$ 25° deadband angle is exceeded.

- A safety system must be designed which monitors overspeed, over or reverse current, vibration, yaw error, pitch system hydraulic fluid level, bottle pressures, temperatures, and microprocessor failure. This safety shutdown system must be designed with a primary and, in some cases, a redundant set of sensors to effect a safety shutdown by feathering the blades and de-synchronizing the generator.

- The MOD-OA WTG must be capable of operating in the manual, automatic, and remote control modes, including unattended operation to synchronize and automatically disconnect the system as required.

- The automatic control system, using a microprocessor, must be capable of a) monitoring wind conditions and controlling rotor speed and power level; starting, synchronizing, controlling normal operations, and stopping the wind turbine in a safe manner, b) monitoring essential parameters throughout the wind turbine to assure that components are operating within specified tolerances, and c) providing a remotely located operator with the capability of starting, stopping, and monitoring the performance of the wind turbine. Thus, the automatic control system must be designed to interface with the blade pitch control, yaw control, safety, and remote control and monitoring systems.

- The remote control and monitoring system must be designed so that it provides an interface between the wind turbine and a remote operator, and so that it serves as a control link, status indicator, and performance monitor.

- In conjunction with these control system designs, specific data are required for controlling the operation and monitoring the performance of the wind turbine. Thus, one of the design requirements for the control systems is to specifiy the types of data required to be supplied by the instrumentation and data acquisition system.

ENGINEERING DATA ACQUISITION

The engineering data acquisition system is composed of instrumentation, remote multiplexer units, a mobile data system, and a stand alone instrument recorder. Instrumentation is required and provided on the rotor, drive train, nacelle, bedplate, tower, at the control building (switchgear), and on the meteorological tower. The three remote multiplexer units are located on the hub, on the bedplate, and in the control building. The mobile data system is utilized periodically, especially during checkout and initial startup operations. The stand alone instrument recorder is provided to record data when the mobile data system is no longer at the site.

The engineering data acquisition system was designed to satisfy several system design requirements. In addition to the requirements discussed below, further details on the specific design requirements for the components of the engineering data acquisition system are presented in Section 8.0. The overall design requirements for the engineering data acquisition system were as follows:

- Develop an engineering data acquisition system that can be used to determine and/or monitor aerodynamic (e.g., power versus wind speed and drive train efficiency), electrical,

structural (e.g., mean and cyclic loads), control system, and utility interface performance. Also, this system must be capable of determining and monitoring the status of various mechanical and electrical components, and the associated environmental and safety related instrumentation.

- The data acquisition system must be an upgraded version of the MOD-0 data system and include up to 96 channels of instrumentation.

- In conjunction with the design and development efforts being performed in the mechanical, electrical, and control system areas, select and specify the essential parameters that are to be monitored by the data acquisition system and the allowable tolerances for these parameters.

- Identify the form in which data are to be collected, evaluated, and stored.

ENVIRONMENTAL

The environmental system design requirements discussed below are applicable to more than one of the other categories of design requirements, e.g., mechanical components and systems, electrical components and systems, and control systems. The environmental design requirements for the MOD-0A WTG system were as follows:

- Operating temperature range of -10°F (-23°C) to +120°F (49°C).

- Design the WTG to sustain, with the blades feathered, a maximum hurricane wind speed of 125 mph (55.9 m/s) at a 30 foot (9.1 m) elevation [150 mph (67 m/s) at the hub] at any angle of attack.

- Specific design requirements/considerations for rain, snow, hail, ice buildup (particularly with respect to the blades), and high humidity, and for subsequent -0A WTGs, salt (sea) water atmosphere.

- Provide lightning strike protection so as to safely transmit lightning strikes anywhere on the system to the ground; this was to include the selection and use of a specific lightning strike model.

- Design requirements/considerations for seismic loads and windborne objects, including dust storms and sand storms.

- Additional considerations of some of the above types of environmental conditions during storage, transportation, and installation.

SAFETY AND FAILURE MODES AND EFFECTS ANALYSIS

Several system design requirements fall under the categories of safety and failure modes and effects analysis (FMEA). In general, these requirements are applicable to the design of components and systems in the mechanical, electrical, control, and data acquisition areas. These safety and FMEA design requirements were as follows:

- Implement a safety program which reviews all mechanical and electrical components and systems and which identifies, evaluates, and either eliminates or controls all undesirable hazards with the potential to: injure personnel, visitors, or the general public; damage the system; or cause loss of program objectives.

- The safety design criteria shall be that no major damage, or personnel, visitor, or general public hazard should occur because of a single point failure or a single failure following an undetected failure.

- Develop a safety shutdown system capability which monitors specific parameters, as discussed above under the control and data acquisition system design requirements.

- Perform a Failure Modes and Effects Analysis on all mechanical and electrical systems and components to identify those critical failure modes that could be hazardous to life or result in injury or major damage to the WTG system.

ADDITIONAL CONSIDERATION

Although not a design requirement, the desired goal for the availability of the MOD-OA WTGs (defined as the ratio of the hours of synchronous operation to the hours between cut-in and cut-out wind speed) was selected as 0.9, and this goal was selected after the design was frozen. Actually, the intent of the design and analysis efforts performed was to build in as much reliability as possible in an attempt to keep the WTG operating as close to 100 percent of the time that the wind was within the specified operating range.

3.2 SYSTEM SPECIFICATIONS

Detailed system specifications, including some component specifications, for the MOD-OA WTG design have been developed which satisfy the above system design requirements. A few of these system and component specifications were extracted from previous reports.[21, 22] Most of these system specifications were derived from other sources such as, engineering drawings, purchase specifications, and the detailed discussions of components and systems in this report. The purpose of this section is to summarize the key, relevant specifications for the MOD-OA wind turbine design.

Presented in Table 3.2-1 are the system and component design specifications for the MOD-OA WTG. These detailed specifications have been categorized under the following major headings, with the appropriate page number of Table 3.2-1 indicated:

These design specifications were prepared so as to provide an overall understanding of the type, size, shape, materials, manufacturer, performance, operating modes, operating sequence, location, equipment capabilities, etc., as they pertain to the above-mentioned components and systems. Further details on the component and system design specifications are presented in Sections 4.0, Design and Analysis; 8.0, Engineering Data Acquisition; 2.12, Predicted Performance; and 2.14, Weight Summary.

TABLE 3.2-1: SYSTEM SPECIFICATIONS FOR
Page 1 of 11 MOD-OA 200 kW WTG

PERFORMANCE

Rated Power.	200 kW	
Wind Speed at:	30 ft. (9.1 m)	hub, 100 ft. (30.5 m)
Cut-in	6.9 mph (3.1 m/s)	9.5 mph (4.2 m/s)
Rated.	18.3 mph (8.2 m/s)	22.4 mph (10.0 m/s)
Cut-out.	34.2 mph (15.3 m/s)	40 mph (17.9 m/s)
Maximum design (Hurricane)	125 mph (55.9 m/s)	150 mph (67.0 m/s)
Power Profile (Curve of Generator Power Output vs Wind Speed). . . .	See Figure 1.2.1-1	

ROTOR (GENERAL)

Type	Horizontal-axis
Number of Blades	2
Diameter	125 ft. (38.1 m)
Rotor area (circular area swept by rotor).	12,272 ft^2 (1140. m^2)
Speed, (constant, when synchronized)	40 rpm
Direction of Rotation.	Counterclockwise (looking upwind)
Location Relative to Tower	Downwind
Cone Angle (Swept downwind).	7°
Tilt Angle (Inclination of Rotor Axis Relative to Horizontal) . . .	0°

BLADE

Length	59.9 ft (18.26 m)
Materials:	
Primary.	2024T3 Aluminum
Cylindrical blade root shank . . .	4340 Steel
Weight (per blade)	2350 lbs (1066. kg)
Airfoil.	NACA 23000
Twist (non-linear)	33.8°
Area of one blade projected on swept circular area	179. ft^2 (16.6 m^2)
Solidity (airfoil area density). . .	2.9%
Root Chord	4.5 ft (1.37 m)
Tip Chord.	1.5 ft (0.46 m)
Chord Taper.	Linear
Root Thickness	1.5 ft. (0.46 m)
Tip Thickness.	2.0 in. (5.1 cm)
First flapwise natural frequency (normal to chord plane).	1.5 Hz
First chordwise natural frequency (in the plane of the chord). . . .	2.9 Hz
Designer	Lockheed California Co.
Manufacturer	Lockheed Aircraft Service Co.

TABLE 3.2-1: SYSTEM SPECIFICATIONS FOR
Page 2 of 11 MOD-OA 200 kW WTG

BALANCE OF ROTOR (HUB, PITCH CHANGE MECHANISM, AND PITCH HYDRAULIC SYSTEM)

Hub:	
Type of Hub	Rigid
Material	4340 steel forging
Envelope dimensions (radial)	32.8 in. (0.833 m) x 32.0 in. (0.813 m)
Length (axial)	30.6 in (0.777 m)
Weight (machined)	1760 lbs (798 kg)
Pitch Change Mechanism:	
Method of Power Regulation	Variable Pitch (Full span)
Pitch Actuator	Hydraulic / pressure control valve / rack and pinion / gears
Location	Hub, inside prop cone
Maximum Rate of Pitch Change	8° / sec
Backup System	Accumulator and N_2 gas bottle pressure
Weight	2540 lbs (1150 kg)
Pitch Hydraulic System:	
Pump	10 hp (7.46 kW) high pressure pump, motor driven
Location	Nacelle (nose cone)
Routing	Through rotating hydraulic union and shaft inside low speed shaft to pitch change mechanism
Rotating Hydraulic Union: Manufacturer / Model No.	Deublin Co. / 255-198

LOW SPEED SHAFT, BEARINGS AND COUPLING

Low Speed Shaft:	
Type	Hollow
Material	Grade 4340 Alloy Steel
Outside Diameter	10.23 in (26.0 cm)
Max. outside diameter (at hub interface)	25.5 in. (64.8 cm)
Fillet radius (near hub interface)	2.50 in. (6.4 cm)
Length	58.8 in. (1.49 m)
Speed	40 rpm
Bearings:	
Type	Spherical Roller Bearings
Manufacturer / Model No.	Torrington / 260SD32
Dynamic capacity of each bearing	530,000 lb (2.36×10^6N)

TABLE 3.2-1: SYSTEM SPECIFICATIONS FOR MOD-0A 200 kW WTG
Page 3 of 11

Coupling:

Manufacturer / Model No.	Falk / No. 1070G

SPEED INCREASER (TRANSMISSION OR GEARBOX)

Type	Three-stage conventional (parallel shafts)
Input speed	40 rpm
Ratio	45:1
Output Speed	1800 rpm
Rating	450 hp (336 kW)
Nominal Power Level	360 hp (268 kW)
Input Shaft Diameter	9.0 in. (22.9 cm)
High Speed Shaft Diameter	3.0 in. (7.62 cm)
Mechanical efficiency	$\geq$ 90%
Weight	5500 lbs (2500 kg)
Height, Width, and Depth (Axial)	34.5 in (87.6 cm), 54. in (137 cm), 30 in (76.2 cm)
Manufacturer	Horsburgh & Scott Co.

HIGH SPEED SHAFTS, ROTOR BRAKE, BEARINGS, COUPLINGS, FLUID COUPLING, AND BELT DRIVE

High Speed Shafts:

Speed	1800 rpm
Diameter	2.75 in (6.98 cm)
Length of intermediate shaft	31.6 in (80.3 cm)
Length of pulley drive shaft	44.3 in (112.0 cm)

Rotor Brake:

Type	Disk with two calipers
Caliper Manufacturer / Model No.	Horton Co. / No. 9336
Location	Downwind, and on high speed shaft, of speed increaser
Speed of Brake Disk	1800 rpm
Disk Dimensions	18. in (45.7 cm) diameter, 0.50 in (1.27 cm) thick
Material	Mild Steel
Actuation	Pressurized N_2
Braking Torque	25,000 in-lbs (2820 Nm)
Stopping Time	6.3 sec (Critical shutdown from 1800 rpm)

Bearings:

Quantity / Type	2 / Pillow Block Assembly
Manufacturer / Model No.	Torrington / FSAF-22517A

TABLE 3.2-1: SYSTEM SPECIFICATIONS FOR
Page 4 of 11 MOD-OA 200 kW WTG

Couplings:	
Quantity / Type.	2 / Gear
Manufacturer / Model No.	Zurn / FS-102
Fluid Coupling:	
Type	Vaned Impeller and Vaned Runner
Manufacturer / Model No.	Am. Std. / SS-550
Diameter of Casing	25 in. (63.5 cm)
Length	13 in. (33.0 cm)
Percent Slip	2.25 (approx.)
Belt Drive:	
Pulley Sheaves: Manufacturer / Model No.	Browning Grip Belt / 10U5V132
V-Belts Manufacturer / Model No. .	Browning Grip Belt / 5V1060
Number of Belts.	10 max.
GENERATOR	
Type	Synchronous ac
Rating	250 kVA continuous
Power Factor	0.8
Efficiency (min.).	90%
Voltage.	480 V (Three Phase)
Configuration / No. of Poles	4 Wire, Grounded Wye / 4 Poles
Speed.	1800 rpm
Frequency.	60 Hz
Weight	2270 lbs (1030 kg)
Manufacturer / Model No.	KATO Engineering / 200EU9E
Type of Exciter.	Directly Connected Brushless
Insulation	Class B
NACELLE EQUIPMENT (BEDPLATE, NACELLE, TURNTABLE BEARING, SUPPORT CONE, AND MOUNTING FRAME)	
Bedplate:	
Material	SAE 1010-1030 Steel
Length	17.3 ft (5.28 m)
Width (Maximum).	6.67 ft (2.03 m)
Height	2.29 ft (0.70 m)
Center of Gravity of bedplate and all equipment supported by bedplate, including rotor (with respect to tower centerline) . .	3.59 ft (1.095 m) downwind; 0.124 ft (0.038 m) to right looking upwind
Construction	Box Beam Weldment
Weight	8310 lbs (3370 kg)

TABLE 3.2-1: SYSTEM SPECIFICATIONS FOR
Page 5 of 11 MOD-OA 200 kW WTG

Nacelle (Includes Stationary Parts and Rotating Part [Prop Cone or Spinner]):

Material	Fiberglass Shell
Shell Thickness (min.)	0.312 in (0.792 cm)
Length	31.3 ft (9.54 m)
Diameter	7.96 ft (2.42 m)
Supported by	Bedplate or hub (prop cone)
Instrumentation.	Anemometer and wind vane
Number of Sections	4 (nose cone, forward and rear cylindrical shrouds, and prop cone)

Turntable Bearing:

Mounting:

Axis of Rotation	Vertical
Inner Ring	Stationary, attached to support cone
Moment Load.	Applied to Outer Ring

Design Load Capacity and Life Requirements (While Stationary):

Moment (upsetting)	5.4×10^6 in.-lbs. (0.61×10^6 Nm)
Downward	60,000 lbs. (2.67×10^5 N)
Aft.	50,000 lbs. (2.22×10^5 N)
Life	1×10^8 cycles

Short Term Static Loading (Combined):

Moment	9.6×10^6 in-lbs. (1.08×10^6 Nm)
Thrust	80,000 lbs.(3.56×10^5 N)
Inner Ring Bolt Circle Diameter. . .	44.0 in.(1.12 m)
Outer Ring Bolt Circle Diameter. . .	51.0 in.(1.30 m)
Manufacturer	Messinger Bearing
Height of Assembly	3.44 in. (8.74 cm)

Support Cone (or Yaw Cone):

Diameter of base	71 in. (1.80 m)
Diameter at Top.	46.4 in. (1.18 m)
Height	36.9 in. (0.937 m)
Material / Thickness	SAE1020 Steel / 0.50 in (1.27 cm)

Mounting Frame:

Shape (Plan View).	Square
Length of Sides.	7. ft. (2.13 m)
Height (Basic)	14. in (35.6 cm)
Height of Underhung Structure. . . .	28. in (71.1 cm)
Material	ASTM A36 Steel

TABLE 3.2-1: SYSTEM SPECIFICATIONS FOR MOD-OA 200 kW WTG

YAW (ORIENTATION) DRIVE MECHANISM AND BRAKE

Yaw Drive Mechanism:

Type	Motor driven with dual mechanical drives.
Pitch Diameter of Gear	55.2 in (1.40 m)
Yaw Rate	1/6 rpm (1.0°/sec)
Yaw Drive	Electric motors (2)
Rating, Drive Motors, ea.	10 hp (7.46 kW)
Torque Limit (red-line limit on each drive shaft)	160,000 in-lbs.(18,080 Nm)
Shaft Preload	50,000 in-lbs. (5,650 Nm)
Normal Operating Shaft Torque	75,000 ±20,000 in-lbs. (8470 ±2260 Nm)
Gear Drives	Double reduction, self-locking worm drives
Control Deadband	± 25°

Yaw Brake:

Quantity / Type	3 / Hydraulic
Manufacturer / Model No.	Goodyear / SCL-19-2
Location / Attachment	90° apart / bolted to support cone assembly
Brake Disk Dimensions	72.0 in. (1.83 m) diameter, 1.25 in (3.18 cm) thick
Hydraulic Power Source	3/4 hp (560 W) pump, motor driven
Clamping Pressure (hydraulic)	1500 - 2500 psig (10.3 - 17.2 MPa), unregulated, when not yawing
Drag Pressure (hydraulic)	100 psig (0.69 MPa), during yaw maneuver

SLIP RINGS (POWER, INSTRUMENTATION AND CONTROL)

Low Speed Shaft Slip Ring:

Number of Contacts / Rating	36 / 5A, 120V, 60 Hz

Tower Slip Ring:

Number of Contacts / Rating (Generator Output)	4 / 350A, 480V, 60 Hz
Number of Contacts / Rating (Higher Level ac Power & Control)	10 / 50A, 480V, 60 Hz
Number of Contacts / Rating (Instrumentation, Control, and 120V Distribution)	90 / 5A, 120V, 60Hz
Manufacturer	Fabricast
Type	Spring Loaded Silver Graphite Brushes on Bronze Rings

TOWER AND FOUNDATION

Tower:

Type	Four-legged pipe truss
Height	93 ft (28.3 m)
Hub Height (Rotor Centerline)	100 ft (30.5 m)
Ground Clearance for Blades	37.5 ft (11.43 m)
Base Span	30 ft (9.14 m)
Cap Span	7 ft (2.13 m)
Access to Top	1500 lb. (680 kg) Hoist
Materials	ASTM A53 pipe and A36 plate steel
Construction	Welded 8 in. (20.3 cm) extra strong vertical pipes and 4 and 5 in. (10. 2 and 12.7 cm) pipe horizontal and diagonal members
Erection mode	Crane
Fundamental Natural Frequency	2.2 Hz

Foundation:

Type	Reinforced Concrete Slab
Dimensions	34 ft (10.36 m) square
Thickness	4 ft (1.22 m)

SWITCHGEAR

Type	Indoor, dead front, metal enclosed
Voltage	480V (Three Phase)
Configuration / Frequency	4 Wire, Grounded Neutral / 60 Hz
Fault Current	22 kA rms symmetrical
Rating of Bus	600A, 480V

TRANSFORMER AND OIL CIRCUIT RECLOSER

Transformer:

Type	3 Phase, Dual Ratio, Oil Cooled, Padmounted Distribution
Rating	300 kVA
Configuration (Primary / Secondary)	2400 V Delta / 480V Delta
Voltage Taps	5 Taps at 2-1/2 % ea.
Manufacturer / Model No.	General Electric / Compad III

Oil Circuit Recloser:

Type / Manufacturer	W (Oil) / McGraw-Edison
Rating	560 A, 14.4 kV
Interrupting Capacity	10 kA rms Symmetrical

TABLE 3.2-1: SYSTEM SPECIFICATIONS FOR
Page 8 of 11 MOD-OA 200 kW WTG

CONTROL SYSTEMS (BLADE PITCH CONTROL, GENERATOR CONTROL, YAW CONTROL, MICROPROCESSOR, SAFETY SYSTEM, AND REMOTE CONTROL AND MONITORING)

Blade Pitch Control:

Type	Closed loop servo
Operating Modes.	Direct control of pitch angle; closed loop pitch control to regulate speed; and closed loop generator power control, supplemented by wind speed compensation (wind feed forward)
Manufacturer / Model No.	BAFCO Inc. / 846

Generator Control:

Type	Voltage/VAR/PF controller and synchronizer
Operating Modes:	
Manual	Field excitation adjustable from zero to rated
Automatic.	Sense generator voltage within 2% of rated, from no load to full load, at 0.8 power factor
Static Voltage Regulator Manufacturer / Model No.	Basler Electric / SR4A
Manual Voltage Control Module Manufacturer / Model No.	Basler Electric / MVC104
VAR/Power factor controller Manufacturer / Model No.	Basler Electric / SCP250
Synchronizing Device Manufacturer / Model No.	Basler Electric / PRS370 auto-synchronizer

Yaw Control (Orientation):

Yaw Rate	1°/sec
Operating Modes.	Automatic and Manual
Method / Filter.	Standard relay logic / 10 sec. time constant
Deadband	± 25°
Operating Sequence	If 10 second average signal exceeds deadband, release clamping brake pressure to drag brake pressure (See "Yaw Brake"), when pressure <150 psig (1.034 MPa), start both yaw drive motors, de-energize motors when filtered error is < 7-1/2°; coast to stop (∿2 sec), activate clamping pressure.

TABLE 3.2-1: SYSTEM SPECIFICATIONS FOR
Page 9 of 11 MOD-OA 200 kW WTG

Yaw Drive System Deactivated	When wind is <8 mph (3.58 m/s)
Safety Shutdown.	Initiated when 10 second average yaw error exceeds 40°.
Microprocessor:	
Manufacturer and Model No.	INTEL 8080 central processing unit
Includes:.	16 A/D converters, 12 bits, with a ± 10 V dc input; 12 discrete 120V, 60 Hz inputs; 8 discrete 120 V, 60 Hz, 2A outputs; 8 normally open relay outputs; 6 D/A converters, ± 10 V; 2 digit display; 8 interrupts for start/stop; 256 bytes of RAM; and 2 K bytes of EPROM.
Safety System:	
Type	Redundant, fail-safe, and operates independently of all other control systems
Reliability.	Fail-safe, yet sufficient to prevent unrequired or spurious shutdowns
Types of Shutdown.	Safety; Emergency; and Critical
Primary and Redundant (noted with *) Shutdown Parameters.	Temperatures, vibration*, yaw error*, overcurrent*, reverse power*, hydraulic level, hydraulic pressure, pneumatic pressure*, intrusion, microprocessor, normal overspeed (rotor speed of 42 rpm), and excessive overspeed* (rotor speed of 45 rpm).
Circuit connection for primary / redundant sensors.	Interface and annunciator, with condensed version of annunciator function transmitted to remote control and monitoring station, and relay logic to effect shutdown/sensors wired in series to effect a shutdown independent of primary system, within the nacelle.
Emergency Shutdown Sequence (effected by primary shutdown sensors)	Initiation; Open emergency feather valves (blades move toward feather position at 2.5°/sec) and pitch hydraulic pump turned off (emergency feather bottle will feather blades even if only one of the fail-safe solenoid valves or the servo valve

TABLE 3.2-1: SYSTEM SPECIFICATIONS FOR
Page 10 of 11 MOD-OA 200 kW WTG

	calls for feather); 5 sec time delay (to prevent overspeeding when load is dropped from generator); generator field and synchronizing contactors opened; halt command to microprocessor
Critical Shutdown Detection / Sequence	Rotor speed reaches 45 rpm or a redundant shutdown initiated by vibration or pressure / engage rotor brake (takes $\sim$6 sec to stop the rotor), followed by other shutdown actions
<u>Remote Control and Monitoring:</u>	
Control functions and capabilities .	On/off command pulses and initiating an emergency shutdown
Status indicators.	On/off lights and 6 error conditions detectable by safety system
Microprocessor status.	2 digit display
Performance monitoring	By analog data section, six data channels displayed in digital format
Manufacturer and Model No.	Weston 3200 Series Remote Data Acquisition/Control System
<u>ENGINEERING DATA ACQUISITION (REMOTE MULTIPLEXER UNITS, MOBILE DATA SYSTEM, AND STAND ALONE INSTRUMENT RECORDER)</u>	
<u>Remote Multiplexer Units (RMUs):</u>	
Quantity / Location.	3 / hub, bedplate, control building
Number of data channels (ea.) / filter capability.	32 / 4 pole, low pass active Butterworth filter providing a band width of 40 Hz adjustable measurement ranges
Types of sensor output	Resistance or voltage (including data from copper constantan thermocouples)
Center frequency spacing and frequency range.	500 Hz and range from 1000 Hz to 8500 Hz
<u>Mobile Data System:</u>	
Input patch panel.	Receives six frequency modulated multiplexes
Equipment capabilities	Fourteen-track tape recorder/reproducer (tape recorder records all six multiplexes and IRIG B time signal); frequency modulation discriminators; 16 strip chart recorder channels; spectrum analyzer; analog to digital converter; data compressor; digital computer; and a CRT.

TABLE 3.2-1: SYSTEM SPECIFICATIONS FOR
 MOD-OA 200 kW WTG

Stand Alone Instrument Recorder (SAIR):

Types of Data Channels	3 FM multiplex signals from RMUs and one internally generated IRIG B, time of day, time code signal.
Manufacturer / Model No.	L'Garde Products / 20366 recorder

SERVICE STAND, EQUIPMENT AND PERSONNEL HOIST, AND CONTROL BUILDING

Service Stand:

Supported Weight	44,900 lbs (20,400 kg)
Size (height, length, width)	4.75 ft (1.45 m), 8. ft (2.44 m), 8. ft (2.44 m)
Material	ASTM A36 wide flange structural steel vertical posts with angle supports

Equipment and Personnel Hoist:

Capacity	1500 lbs (680 kg)
Drive.	Self-powered by electric motors
Location	Within framework of tower
Height of Travel	74. ft. (22.6 m)
Speed.	35 ft/min (0.178 m/s)
Manufacturer / Model No.	Spider Staging Sales Co / ST-27 Shafter
Size (height, length, width)	75. in. (1.90 m), 60 in. (1.52 m), 48 in. (1.22 m)

Control Building:

Construction / Provisions.	Steel, self framing design / heating and ventilating
Size (height, length, width)	8. ft. (2.4 m), 12 ft. (3.7 m), 12 ft (3.7 m)
Location	Within framework of tower

DESIGN LIFE

Static components.	50 years
Dynamic components (Except blades*)	30 years

OVERALL WEIGHT

Rotor (including blades)	12,300 lbs.	(5,580 kg)
Above Tower.	45,000 lbs.	(20,400 kg)
Tower.	44,000 lbs.	(20,000 kg)
Total.	89,000 lbs.	(40,400 kg)

*Blades designed to withstand loads measured on MOD-0 WTG

4.0 DESIGN AND ANALYSIS

The basic features and characteristics of the MOD-OA design are described in Section 2.0 of this report. Section 4.0 also describes the features and characteristics but in more depth than what is given in Section 2.0. In addition, for each system covered in Section 4.0, the design requirements are presented along with the rationale used in establishing the final design. The results of analytical work done on each system are also presented. These results follow after the design descriptions given in this section for each respective system.

The design of the overall assembly of the machine is described on NASA Dwg. Nos. CR758862 and CR758863 (1015F01).

The drive train (mechanical system that drives the generator by utilizing wind energy) has been analyzed for torsional stiffness and for mass moment of inertia. The table below presents the results of this analysis for various components of the drive train.

	Speed (RPM)	Torsional Stiffness (10^8 lb-in/rad)	Mass Moment of Inertia (lb-in-sec^2)
Blades	40	4.39(7)	1,182,000(7)
L S Shaft	40	2.00	7,380(1)
Gear Coupling	40	2.00	4,610(2)
Gear Box	40	3.06	30,200(3)
H S Shaft	1800	18.0	9,020(4)
Belt	1800	7.30	49,200(5)
Gen. Shaft	1800	366.	161,600(6)
Gen. Field	1800	0.52	-----

(1) includes hub assembly
(2) includes gear box
(3) fluid coupling only at speed ratio of 45
(4) includes brake
(5) includes pulleys and 10 belts
(6) includes rotating generator parts
(7) with respect to low speed shaft axis of rotation

4.1 ROTOR AND PITCH CHANGE MECHANISM

The MOD-OA WTG uses a two-bladed, horizontal-axis rotor system. The rotor assembly consists of the blades, a hub, and a pitch change mechanism. The blades are downwind of the tower and are cantilevered from the hub at a 7° coning angle, i.e., each blade is tilted 7° downwind from a vertical plane. The blades are fixed to the hub except for the pitch degree of freedom which is controlled by the pitch change mechanism located within the hub. The hub connects the rotor to the low speed shaft which drives the generator through a step-up gear box (speed increaser). The hub is rigidly bolted to and supported by the shaft which, in turn, is supported from the bedplate through two bearings.

The MOD-OA WTG is operated at a constant rotor speed of 40 rpm. The power output, as a function of wind speed, is regulated by hydraulically varying the pitch angle of the blades. At wind speeds below cut-in and above cut-out, the rotor blades are placed in a feathered position and no power is produced. The rotor diameter is 125 feet (38.1 m) and rotation is counterclockwise looking upwind.

4.1.1 BLADES

Each MOD-OA wind turbine blade is a 59.9 foot (18.3 m) long aluminum structure, which is, in many respects, similar to an airplane wing. The blade has leading and trailing edge structure, formers, stringers, ribs, webs, and skin. However, the size of the blades, the taper, twist, contour, balance, weight, flexural requirements, and operating conditions make them unique. The blades are entirely aluminum except for the root fitting which is steel. Each blade conforms to a prescribed aerodynamic shape that has a large twist and taper. The total twist is 33.8°. The blade chord length varies from 4.5 feet (1.4 m) at the root to 1.5 feet (0.5 m) at the tip. Blade thickness varies from 1.5 feet (0.5 m) at the root to 2 inches (5.1 cm) at the tip.

Previously, three similar blades were built for the MOD-0 WTG. Two new MOD-OA blades, SN-1004 and SN-1005, were fabricated for the Clayton machine. During early operational experience with the MOD-0 machine, measured blade loads were higher than the loads used to design the blades. Therefore, these new MOD-OA blades were redesigned to carry higher loads. The size and shape of these MOD-OA blades can be seen in Figure 4.1.1.-1 which shows final assembly of the nacelle. Figure 4.1.1-2 shows one of the blades during final non-destructive testing at Lockheed.

4.1.1.1 REQUIREMENTS

The blade design requirements are summarized in Table 4.1.1-1. The requirements include the blade dimensions, materials, and the airfoil type, as well as the flapwise (normal to chord plane) and chordwise (in chord plane) cantilever natural frequencies. Figure 4.1.1-3 shows the design planform of the blade. Many additional details of the blade design were set, including the thickness and chord distribution, the twist, the tolerances, the center of mass, a flutter requirement, and the goal of a design life of 50,000 hours at rated conditions (case 1, below).

Operation at four blade loading cases was specified for design and analysis. The basic blade design condition, case 1, is 40 rpm with a wind velocity of 18* mph (8.0 m/s). Case 2 is a sudden wind gust from 18* mph to 60* mph (8.0 m/s to 27.0 m/s) with no change in blade speed or pitch. Case 3 is a control failure from case 1 where the blade is suddenly feathered. Case 4 is a sudden drop in wind velocity to zero from case 1 without change in blade speed or angle.

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*Wind speeds at 30 ft (9.1 m) reference height.

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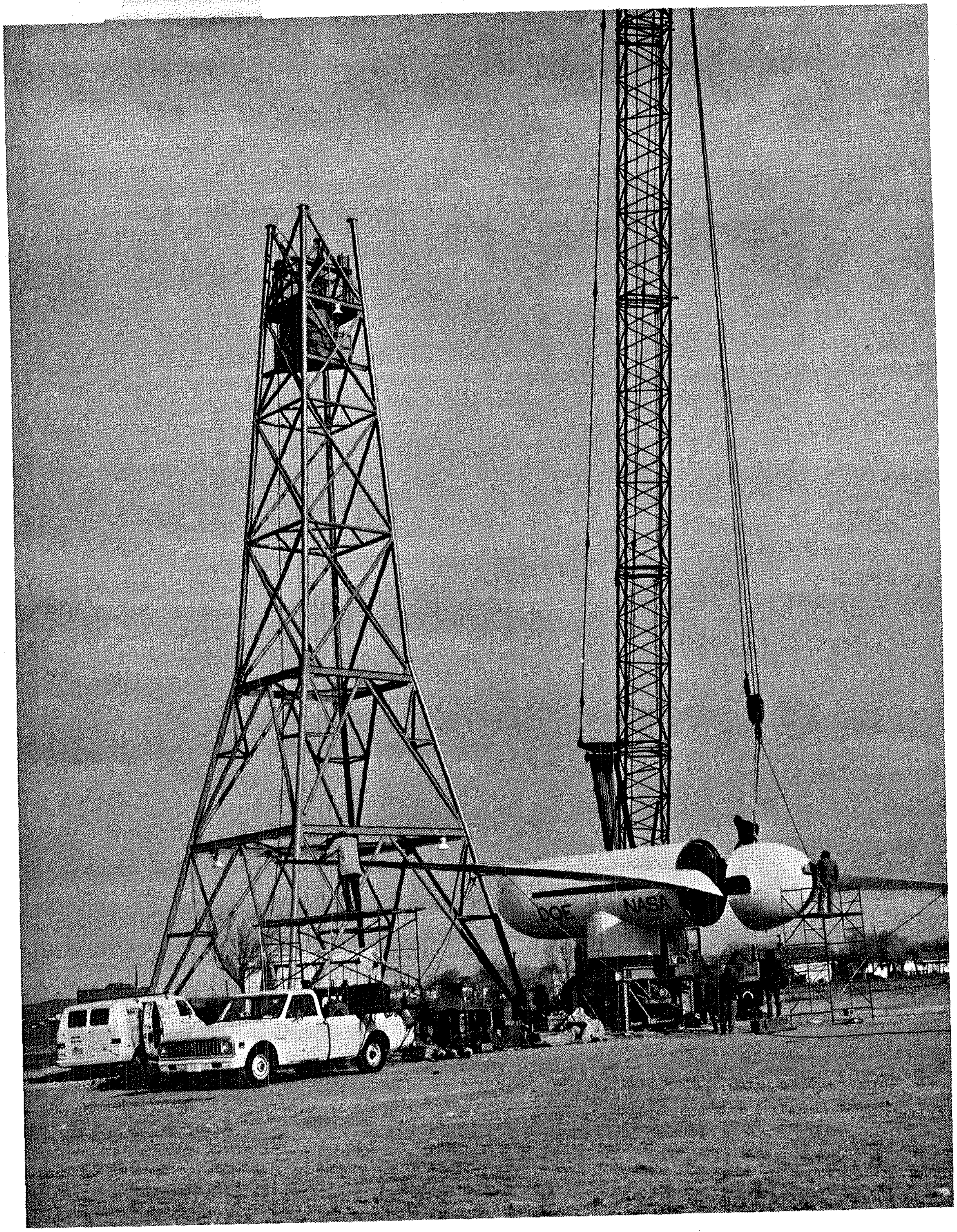

Figure 4.1.1-1. MOD-OA Nacelle Final Assembly

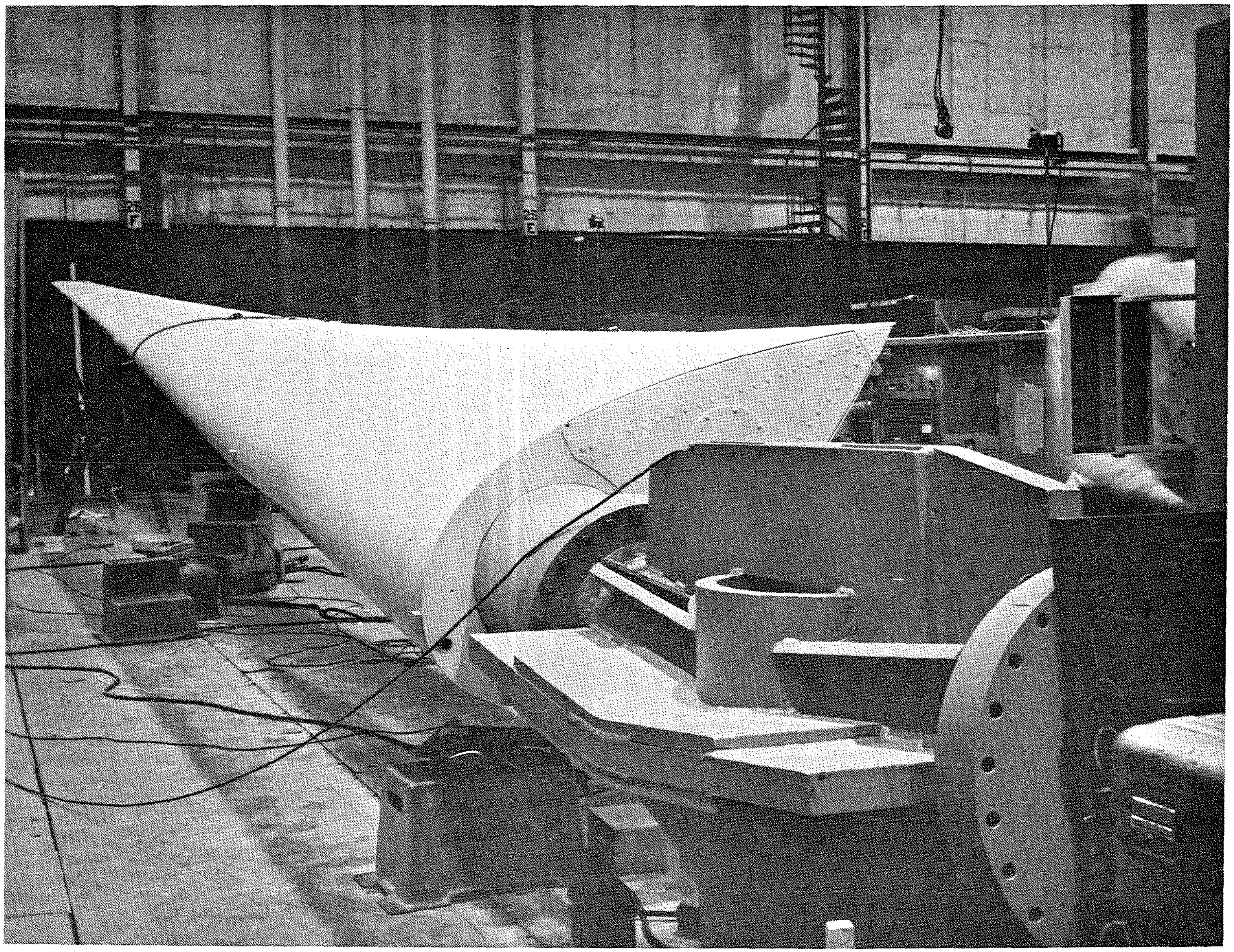

Figure 4.1.1-2. MOD-OA Wind Turbine Blade Non-Destructive Test - LAS Ontario, California

TABLE 4.1.1-1

MOD-OA BLADE DESIGN REQUIREMENTS

DIMENSIONS	
LENGTH	59.9 ft (18.3 m)
TIP CHORD	1.5 ft (0.46 m)
ROOT CHORD	4.5 ft (1.37 m)
CHORD TAPER	LINEAR
TWIST	33.8°
MATERIALS	
ALUMINUM	2024 T3
STEEL	4340
AERODYNAMIC	
AIRFOIL NACA	23000
SOLIDITY	3%
STRUCTURAL DYNAMICS	
FIRST FLAP	1.5 Hz
FIRST CHORD	2.9 Hz

INSTRUMENTATION

STRAIN GAGES:

LOCATION

ROOT END (STATION 40)
MIDSPAN (STATION 370)

MEASUREMENT

FLAP & CHORD BENDING
TORSION

MECHANICAL INTERFACE

CIRCULAR BOLTING FLANGE
24 - 5/8" DIA. HIGH STRENGTH BOLTS

ELECTRICAL INTERFACE

MS CONNECTOR, 55 PIN

BLADE WEIGHT

2350 lbs. (1070 kg)

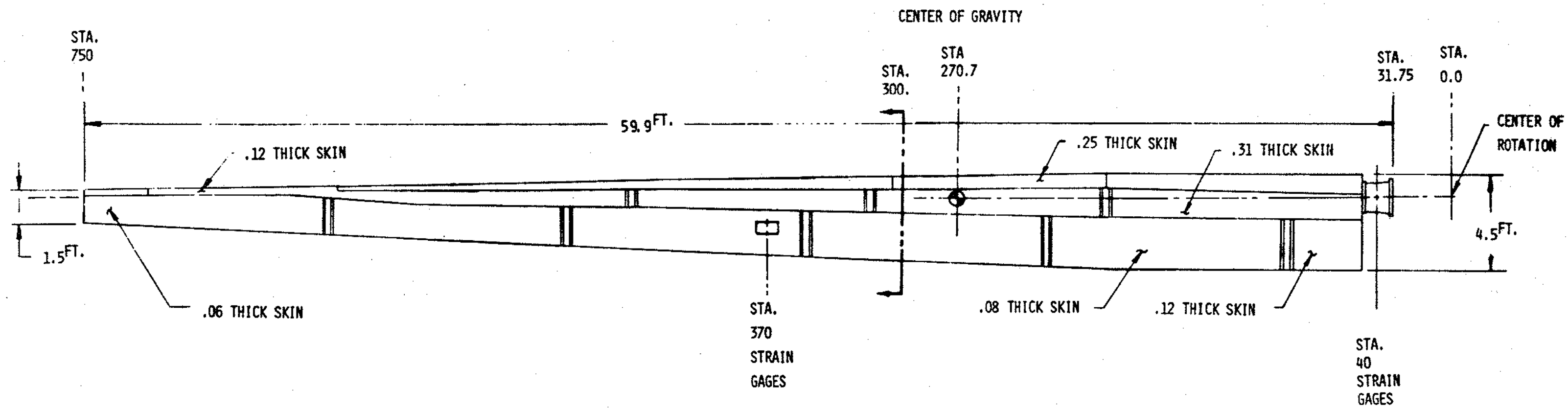

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Figure 4.1.1-3. MOD-OA Blade Configuration - Planform

Environmental requirements include an operating temperature range of -10°F (-23°C) to +120°F (50°C). Provision to prevent water accumulation in the blade was specified as a requirement. The blades are also required to be protected from damage due to moisture. The blades are required to withstand a hailstorm with one inch diameter hail without puncturing the skin or resulting in loss of contour.

Blade vibration and stress analyses were required to be performed by the fabricator. The required analysis results include an interference diagram, vibration modes, vibratory stresses, combined stresses, fatigue limits, and expected life. The stress analysis was required to consider twisting, tension, and bending due to centrifugal forces; aerodynamic loads; gravity; and Coriolis accelerations. Non-destructive tests were also required to verify frequencies, stresses, and deflections, and to calibrate instrumentation.

4.1.1.2 APPROACH

The MOD-OA blade technology has its background in the 100-kW MOD-0 program. The MOD-0 WTG size was selected as being large enough to assess technology and engineering problems in large WTG's within a reasonable project budget. The MOD-0 machine was conceived and built as a test facility rather than as a low cost, fully developed, commercial WTG. Accordingly, many decisions were made early in that design effort based on schedular requirements and likelihood of success. A primary goal of that effort was to begin operation as soon as possible to gain operating experience with a WTG. Therefore the initial MOD-0 hardware designs were to be as conventional and "state of the art" as possible. Also, early design choices were made in a direction toward high reliability whenever it could be predicted with a high level of confidence.

The choice of two rotor blades was made for MOD-0 to simplify the hub and minimize the number of blades. A single blade was considered but quickly discarded because of balance and eccentric load problems. A three bladed rotor of the same diameter could produce somewhat more power, but far less than 50 percent more power at the expense of 50 percent more blades.

Early consideration was given to both upwind and downwind rotor designs. A downward rotor operates in a more severe aerodynamic environment due to the disturbance of the wind profile by the tower wake. Each blade must pass through the wake once per revolution. An upwind rotor, however, has at least two disadvantages relative to the downwind rotor. First, sudden deflections of the blade due to gust loadings tend to bend the blade toward the tower rather than away from the tower as with a downwind rotor and tower/blade clearance may be difficult to ensure. Furthermore, proper coning of the rotor can produce some cancellation of blade aerodynamic bending moments by centrifugal force. However, coning cannot be used in an upwind rotor. It was decided that MOD-0 would initially use a downwind rotor, but might be used later to test upwind rotors.

A hinged, "teetering," rotor was not initially considered for MOD-0. After discovering that Hütter's WTG had such a rotor, the idea was examined.[35] The teetering rotor has substantial advantage over the hingeless rotor,

theoretically. These advantages lie in the area of blade stress and fatigue life and tower loading. Because of the complexity of the analysis of such a concept and the possibility of structural instability occurring, it was decided to use the rigid hub rotor.

Various blade materials and fabrication technologies have been considered for WTG's to date. These have included aluminum, steel, fiberglass, wood, prestressed concrete and a few others. The aluminum blade was selected for the initial set of MOD-0 blades because existing wing structure technology could be directly applied in the design, analysis, and fabrication. Additional development effort will eventually lead to the optimum blade, but again, expediency played a role in the initial MOD-0 choice.

The MOD-0A blade selection was made after MOD-0 began operation but before testing of the original rotor was really complete. The MOD-0 rotor was found to be basically satisfactory and, since the overall objective of the MOD-0A program was to obtain early operation and performance data while gaining experience in a utility environment, the chosen blade design was based heavily on MOD-0. The MOD-0A blades are geometrically similar to the MOD-0 blades. MOD-0A is intended to operate for long periods of time and will test the fatigue endurance of wind turbine components long before comparable experience is accumulated on MOD-0. Therefore, since MOD-0 experienced higher than predicted blade loads,[36, 37] structural modifications were made to extend the fatigue life of the MOD-0A blades.

4.1.1.3 SELECTED DESIGN

The 125 foot (38.1 m) diameter hingeless rotor has two aluminum blades designed to provide 200 kW of shaft power at design conditions.[38] The blades have a 33.8 degree nonlinear twist with a NACA 23000 series airfoil. Externally they are identical to the MOD-0 blades.[39,40,41,42] The blade design requirements were summarized in Table 4.1.1-1. The envelope dimensions are summarized in Figures 4.1.1-3 and 4.1.1-4. The blade chord, thickness, and twist are shown, respectively, in Figures 4.1.1-5, 4.1.1-6 and 4.1.1-7.

Figure 4.1.1-8 shows a cross section of the blade, taken at station 300*, also called out in Figure 4.1.1-3. The forward portion of the cross section is called the D-spar. The aft portion of the cross section is called the trailing edge. The D-spar is a heavier and stronger portion of the blade and, as a result, it carries the majority of the applied loads. Angle stringers and ribs as shown are needed to prevent panel buckling of the 0.08 inch (0.20 cm) and the 0.31 inch (0.79 cm) thick outer skins due to compressive loads.

Detail A, called out in Figure 4.1.1-8, is shown in Figure 4.1.1-9. This shows a typical method of attaching the angle stringers to the D-spar skin and rib. The steel Hilok fastener is an aircraft type of high strength bolt. Close tolerance holes must be prepared so that there is an interference fit between each fastener and the hole. The interference fit allows the Hilok fastener to carry high shear loads. Aluminum rivets are typically used in the trailing edge portion of the blade.

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*Station numbers refer to the distance, in inches, from the axis of rotation of the blade.

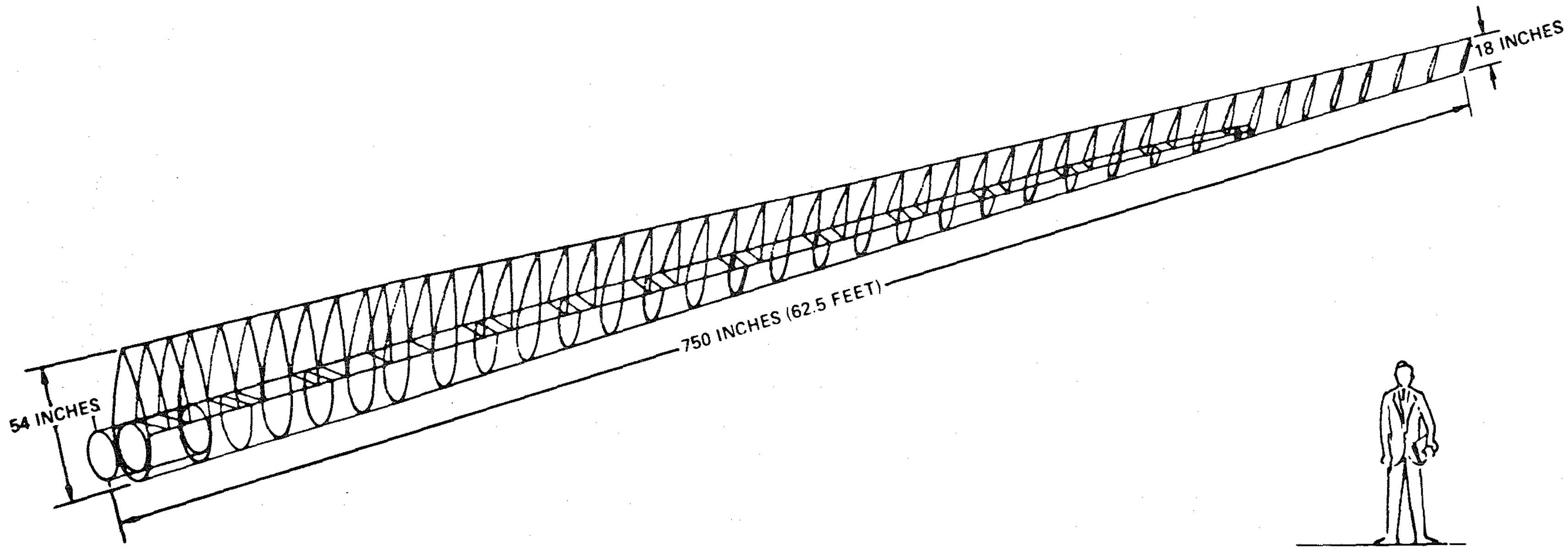

Figure 4.1.1-4. MOD-0A Wind Turbine Blade Geometry

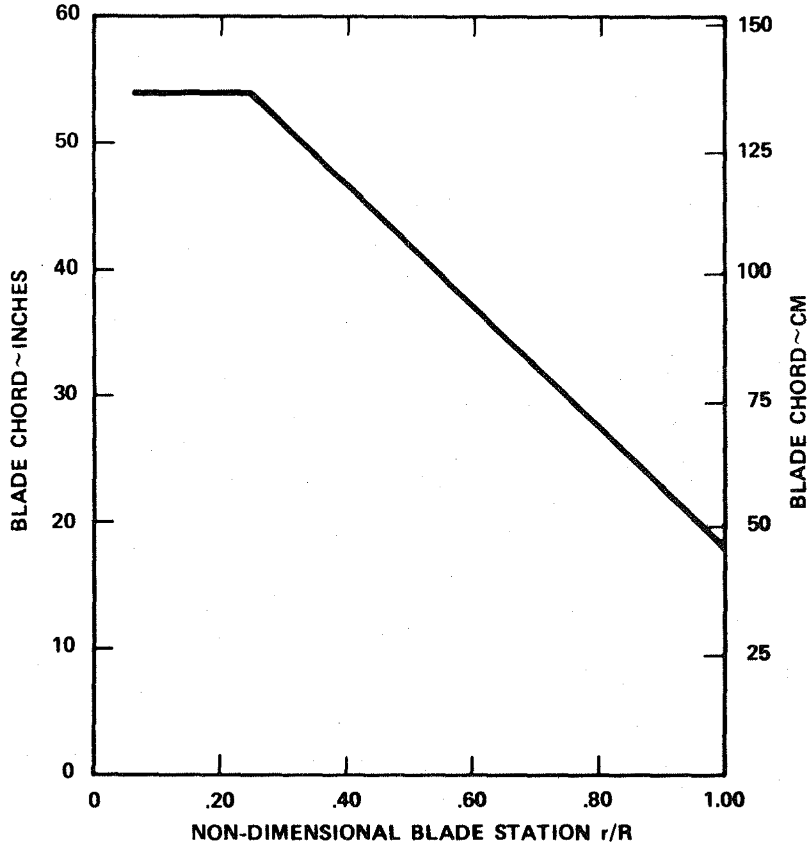

Figure 4.1.1-5. Blade Chord Distribution

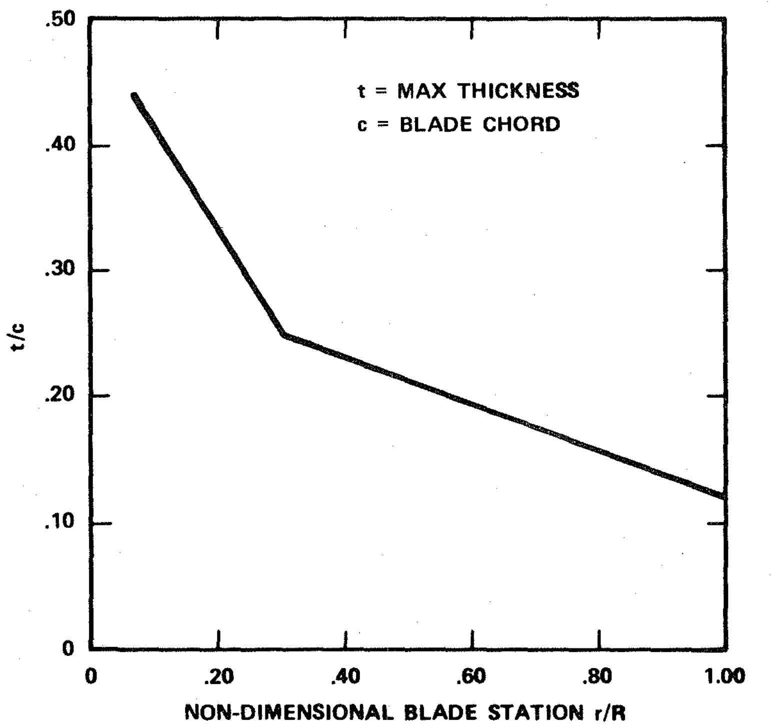

Figure 4.1.1-6. Blade Thickness Distribution

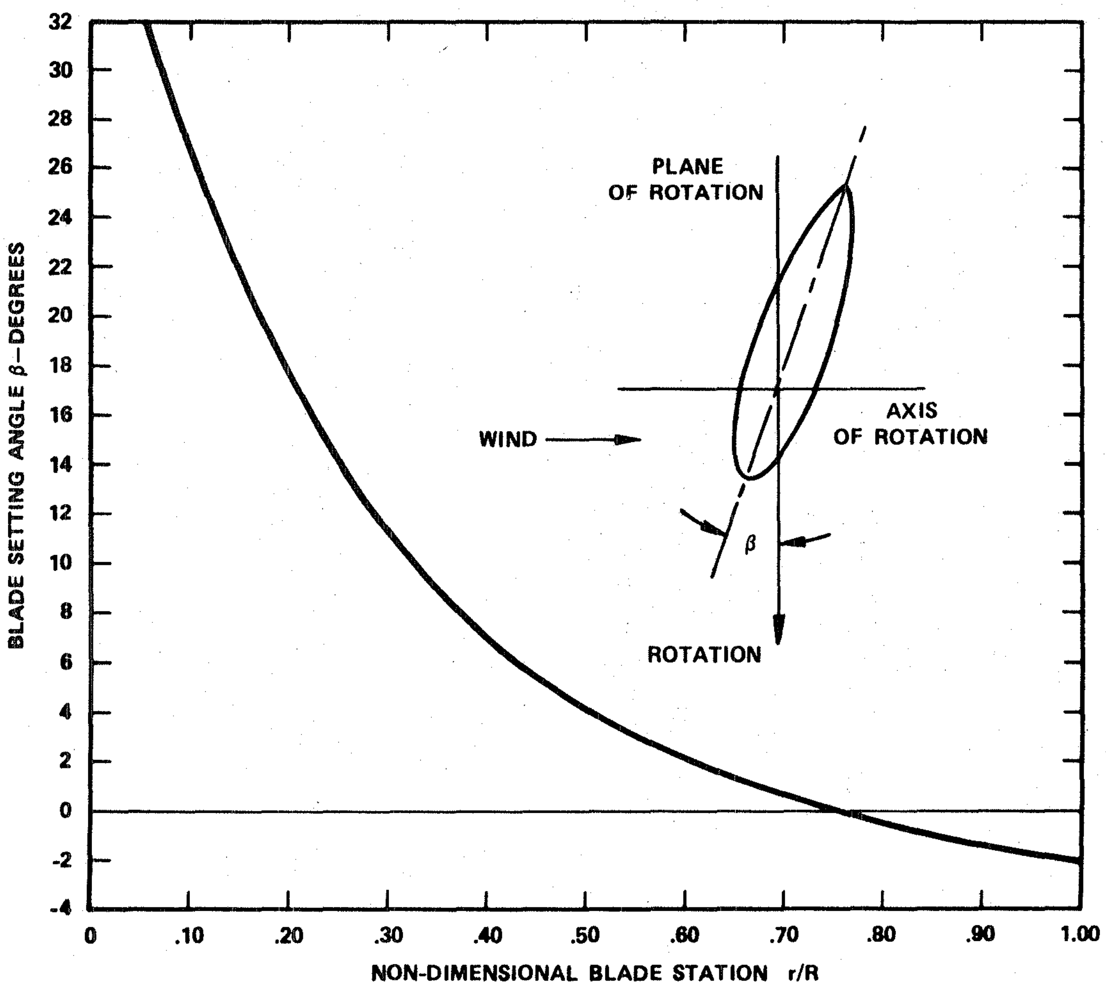

Figure 4.1.1-7. Blade Setting Angle β (Twist)

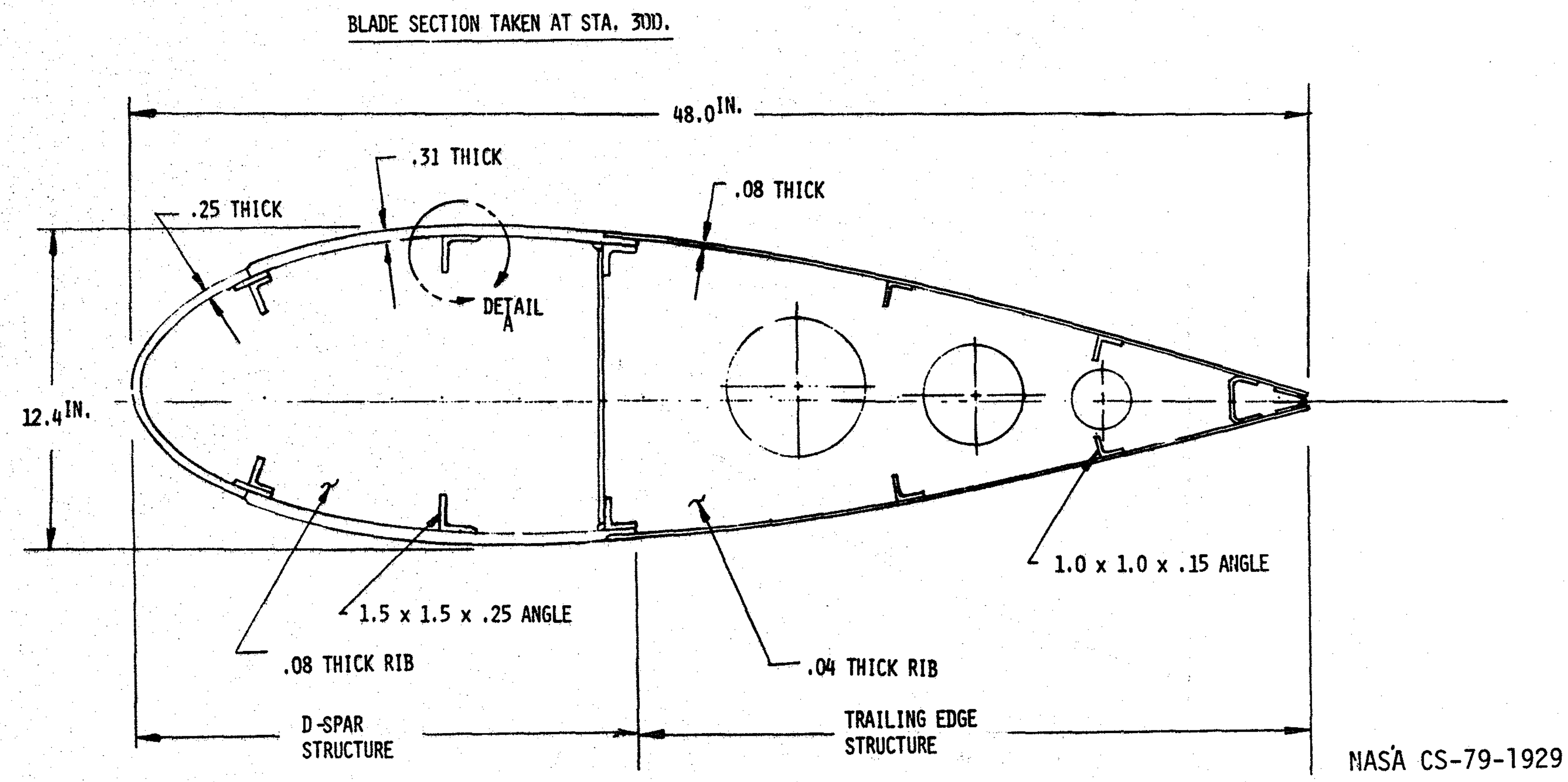

Figure 4.1.1-8. MOD-OA Blade Typical Cross Section

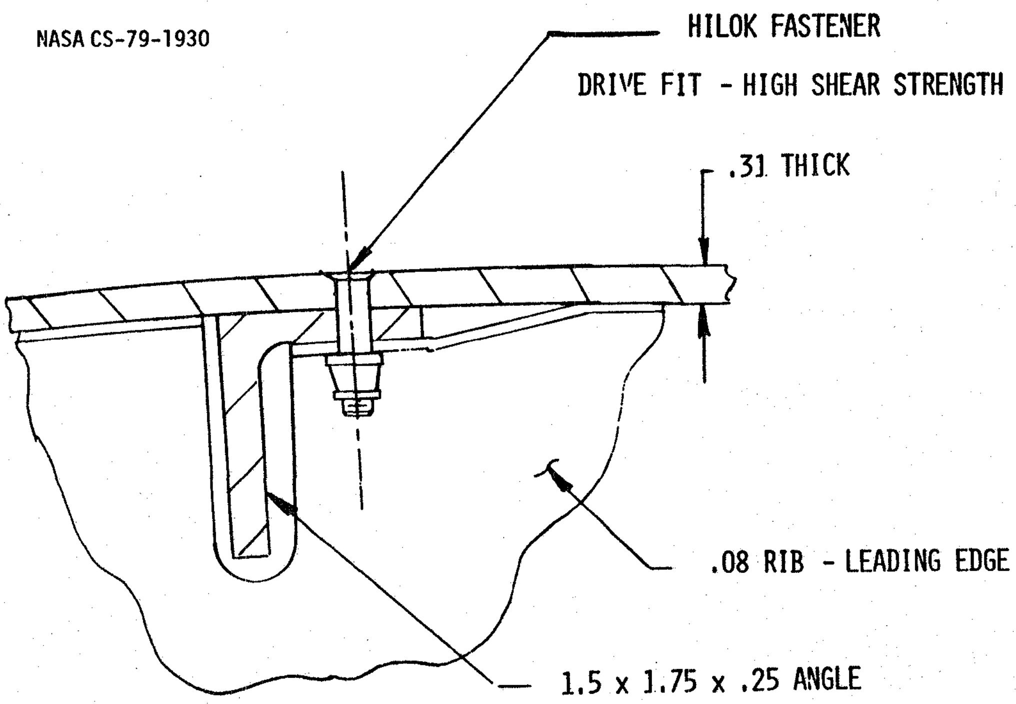

Figure 4.1.1-9. MOD-OA Blade Fastener Detail A

Figure 4.1.1-10 shows the design details of the root end of the blade. A steel cylindrical tube slides through the rib at station 48* and is bolted to the rib at station 81.5. The flange at station 31.75 provides the mechanical interface to the hub of the wind turbine.

The modifications from the MOD-0 design, incorporated to improve the fatigue strength of the MOD-OA blades, can be summarized as:

- The spar cap thickness was increased,
- Several trailing edge thickness changes were made,
- Two stringers were added to each trailing edge surface,
- The root end fitting wall thickness was increased,
- A closure plate was added to an inboard rib to seal the interior of the blade from the hub (to protect the hub mechanism),
- External doublers were added to all D-Spar and trailing edge spanwise structural joints to increase the fatigue life (shown in Figure 4.1.1-3).

The process used to fabricate each blade is labor intensive. Each blade is made up of many individual parts, each requiring a number of hand operations

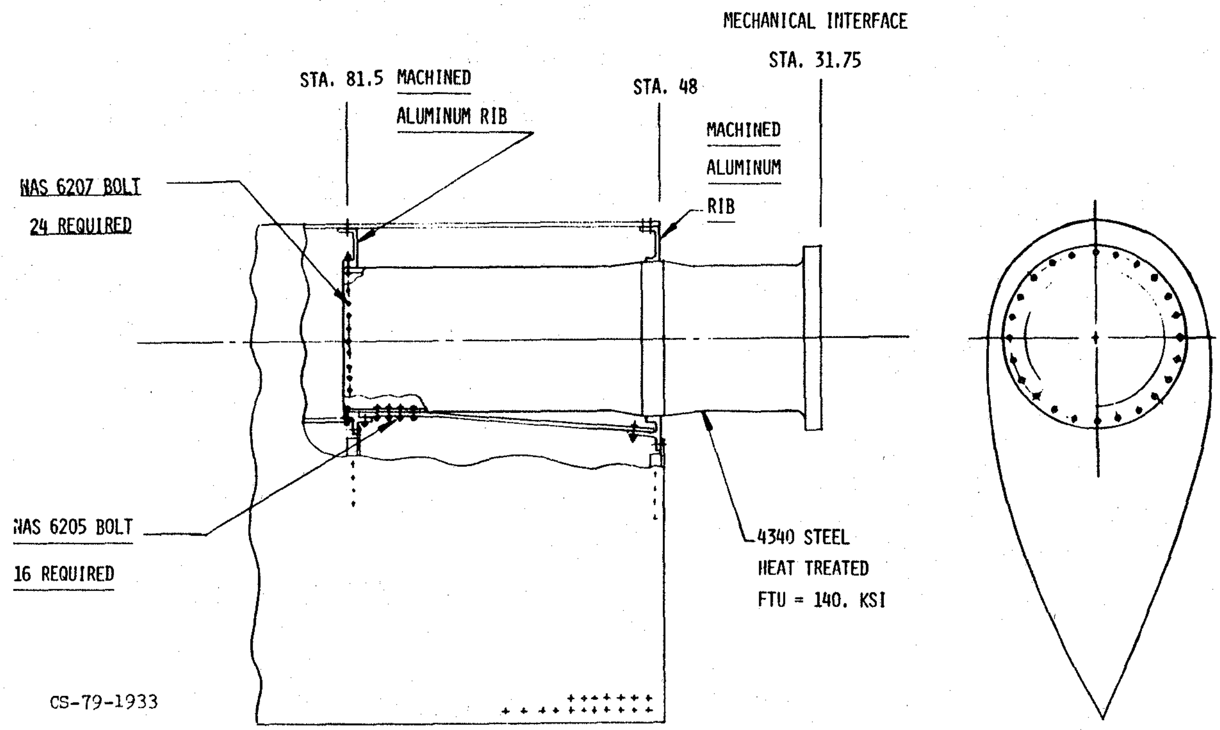

Figure 4.1.1-10. MOD-0A Blade Root End Details

during most phases of fabrication. Examples of this highly labor intensive fabrication and assembly process are as follows:

1. Brake forming of the individual D-spar 0.25 and 0.31 thick skin panels,

2. Hand trimming and fitup of each individual D-spar panel and trailing edge panel,

3. Individually drilling, reaming, and deburring the majority of the 14,000 holes for fasteners.

All blade components were tested for chemical and physical properties to ensure against impurities. In addition to the required test certifications, a copy of the actual test results accompanied each certification. Before assembly was started, the blade fixture, as shown in Figures 4.1.1-11 and 4.1.1-11A was boresighted and adjusted to ensure contour, taper, and rigidity at all stations. The same check was performed at least three times a week during actual blade assembly.

The brake-formed leading edge, assembled in sections, serves as the base for installation of the D-spars, formers, stringers, and ribs. Once installed in the blade test fixture, the leading edge is drawn tight against aluminum sheets fastened to the jig frame on one side and ribs on the other. Stability is ensured by use of turnbuckles and a strap that is secured to the cement floor.

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*Station numbers refer to the distance, in inches, from the axis of rotation of the blade.

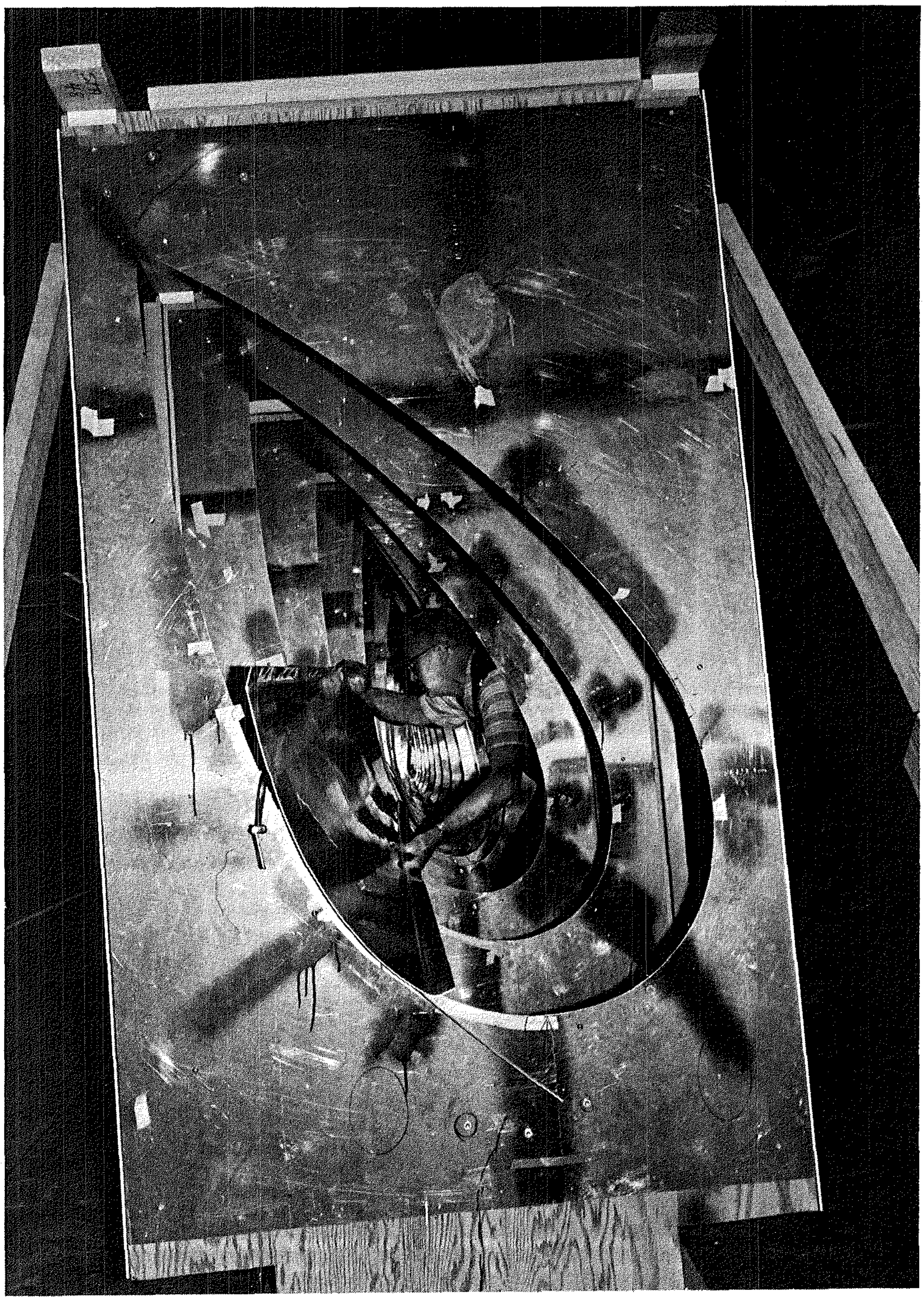

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Figure 4.1.1-11. Blade Fixture Jig Showing Length, Twist and Contour Check Poin

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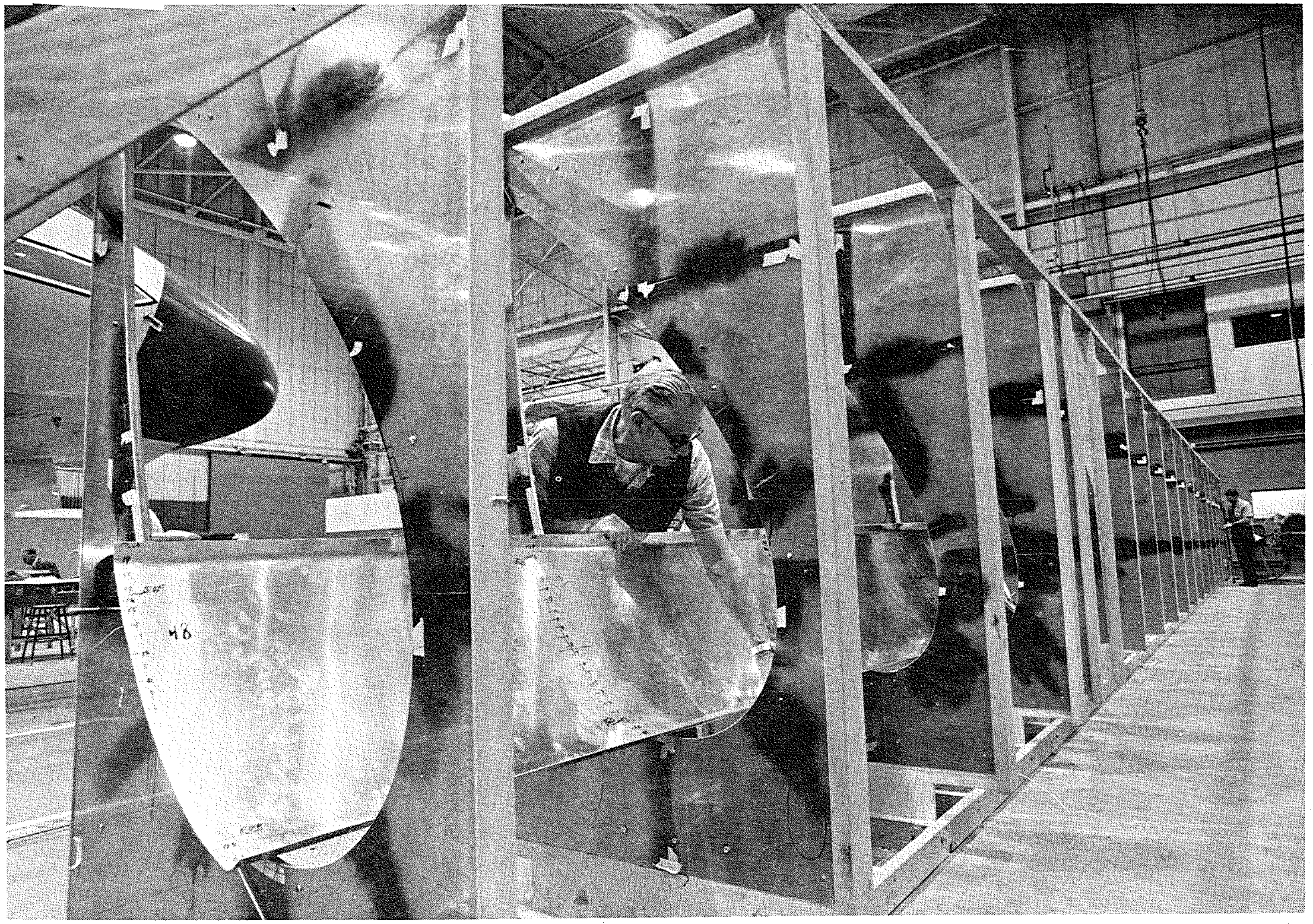

Figure 4.1.1-11-A. Blade Fixture Jig Showing Length, Twist and Contour Check Points

Before any adjustment of the leading edge skin is attempted, each skin is aligned to chord lines marked on the jig and then boresighted adjustments are made as required. Then the first skin segment of the leading edge is trimmed and spliced together with the second skin segment, etc., until the leading edge is one complete assembly. D-spars and ribs are added and secured to the leading edge by Hilok fasteners. Formers over D-spars and stringers on both sides of the leading edge and the formers give additional support to the blade. Thick aluminum skins, varying from 3/16-inch (0.48 cm) just aft of the blade root to 3/64-inch (0.12 cm) at blade tip, are attached to the ribs which run the length of the blade. Except for the steel blade root fitting, all components are constructed of heat-treated 2024 T3 aluminum.

All structural components are wet-sealed at assembly, and frequent inspections are made to ensure an airtight condition exists. Five hollow tubes, one in the apex of the leading edge at the blade root, one centered on ribs at the root segment, and three attached at the blade tip, permit weights to be added or removed to maintain symmetrical balance between each set of blades. In addition, throughout the entire length of the blade (approximately every 22 inches or 55.9 cm) weighted tubes and solid bars are installed in the leading edge to maintain section and segment structural balance.

Strain gages installed in the blade root and in the blade mid-section enable monitoring of flapwise bending, chordwise bending, and torsion moments during operation. The gages are epoxy-sealed and all wires are secured by clamps to the ribs and blade root.

Each blade was tested for (a) deflection and vibration, (b) weight and balance, (c) strain gage accuracy, and (d) X-rayed for defects. Each set of blades was given deflection and vibration, weight and balance, and symmetry checks.

4.1.1.4 SUPPORTING ANALYTICAL RESULTS

In the design of a rotor system, detailed consideration must be given to its dynamic characteristics to ensure a successful design. The items that generally require attention are blade frequency placement, blade flutter including wake effects, torsion flap-inplane stability, stall flutter, gust response, and effect of tower support and control system characteristics on coupled rotor-tower dynamic stability, response, and clearance. Additionally, transient dynamic loads associated with system response during starting and stopping of the rotor system are important considerations.

The MOD-0 analysis plan,[39] therefore, included a detailed blade-frequency analysis, a blade flutter analysis including wake aerodynamics, and an analysis of pitch-flap-lag stability and of the coupled rotor-control-tower dynamic response and stability characteristics. Some of this analysis was redone for MOD-0A, but a complete re-analysis was not made because of the successful MOD-0 program and the similarity of designs. The computer programs used in these analysis efforts included a coupled-flap inplane frequency analysis, a blade flutter analysis program for which full-scale test correlation data was available, and a fully coupled multibladed rotor-body non-linear aerodynamic and dynamic analysis method.

Calculated frequency and mode shapes for the cantilevered blade at the nominal design rotational speed of 40 rpm are: 2.76P, the first flapping mode with primary blade motion normal to the rotor spin plane; 3.62P, the first inplane bending mode with blade inplane response dominantly in the rotational plane of the rotor; and the second flapping mode of motion which occurs at 7.57P. These mode shapes and frequencies show good separation from nP harmonic excitation sources. Also the inplane mode at 3.62P provides excellent placement with respect to the 1P excitations associated with horizontal axis rotor/gravity field. Additionally, it is to be noted that the blade structural axis twist associated with the built-in blade-angle twist distribution results in coupled inplane and flapping motions in the response of the blade natural modes which result in additional aerodynamic damping of the inplane mode.

The blade flutter analysis included examination of the effects of rotor rotational speed, wind velocity, control system flexibility, and blade feathering angle. Rotor speeds from 0 to 80 rpm in combination with wind velocities from 0 to 140 mph (0 to 63.0 m/s) were analyzed. The effects of the wind blowing over the leading edge and trailing edge of the nonrotating rotor were also examined for wind speeds from 0 to 140 mph (0 to 63.0 m/s). Quartering wind condition, where the wind is blowing over the trailing edge at 45 degrees (the most critical case for static divergence), has been analyzed to 200 mph (88 m/s). The results show that the blade system is free from flutter.

Nonrotating blade flutter solutions with wind flow assumed normal to the blade leading edge as well as normal to the blade trailing edge at velocities up to 140 mph (63 m/s) showed no tendency to flutter. This latter result is primarily attributed to the high torsional stiffness of this blade which provides excellent frequency separation between the first blade torsion mode and the fundamental blade bending modes.

The MOD-0 tower was designed by the NASA LeRC Facilities Engineering Division. In recognition of the importance of this experimental facility to the testing of future systems, the possibility of dynamic interaction between the rotor and tower has been minimized by designing a high stiffness and high natural frequency tower. A NASTRAN model of this system has been formulated and the results of the dynamic analysis shows that the first bending natural frequency of the tower/rotor is about 3.75P.

The elastic characteristics of the support shaft, bedplate and tower have been coupled to the rotor system, and blade spectrum frequencies as well as flutter stability solutions obtained. Since the characteristics of the tower support are asymmetric and the rotor is two-bladed, the system cannot be treated rigorously by stationary nonrotating system coordinates with constant coefficients, i.e., time variant equations must be solved. The influence of the elastic support on the rotating blade frequency spectrum and flutter stability margins was investigated using averaged stiffness characteristics. These properties were largely due to shaft flexibility. Again it is found that the system is stable including 100 percent overspeed conditions. Adequate frequency separation is also maintained with respect to higher harmonic excitations at the nominal design conditions.

The Modular Stability Derivative Program (MOSTAB) was developed under contract with the U.S. Army to analyze the performance and flight dynamic characteristics of rotor-craft. Since the development of the original MOSTAB code, many refinements were made leading to the recent MOSTAB-WT (wind turbine) code. The MOSTAB-WT version was used to predict the loads for both MOD-0 and -0A metal blades.

The dynamic loading of the blade in the flapwise direction is dominated by the impulse applied to the blade each time it passes through the tower's wake. It was concluded that the MOD-0 tower was blocking the airflow to a much greater degree than expected and that this was causing excessive flapwise blade loads.[36] Wind tunnel tests of scale models of the tower with and without stairs[43] showed that the blockage was very high with stairs and was greatly reduced when they were removed. Tower blockage was calculated as the ratio of average velocity reduction to the free stream velocity V_0. Removing the stairs reduced the blockage from 0.64 to 0.35. As a result, flapwise blade loads were reduced by about one-third. To further reduce blockage, the MOD-0A tower uses structural pipes for all truss elements.

Examination of the harmonic content of the MOD-0 chordwise blade loads led to the conclusion that excessive loads were caused by nacelle yawing motion. Unexpectedly soft torsional stiffness of the original MOD-0 yaw-drive system produced a yawing resonance which resulted in large lateral motions of the rotor hub. To reduce chordwise loads, it was recommended that the MOD-0 single yaw drive be replaced by a dual drive system. Nacelle motions would then be reduced because of three factors: (1) avoidance of a resonance which was of greatest significance, (2) stiffening the nacelle-to-tower connection and (3) eliminating the free play and non-linearity present in the single yaw drive system. The recommended modifications have decreased both the mean loads and their variation dramatically. This is particularly evident when the gravity cyclic load is recognized as the minimum possible value. Predictions of chordwise load with the yaw modifications were found to be somewhat conservative.

The load calculation methods verified by the MOD-0 experience were used to predict blade loads for the MOD-0A wind turbine. These predicted loads are shown in Figures 4.1.1-12 and -13. As shown in these figures, the strengthened MOD-0A blade should be free of fatigue damage from loads over almost all of its operating range.

The blade fatigue analysis is summarized in Section 4.8.2. The results of the analysis are shown as the dashed lines in Figures 4.1.1-12 and -13. The fatigue analysis concludes that the blades can withstand these loads indefinitely. The maximum "red line" loads are listed in Table 4.1.1-2. These are the highest loads that the blades can withstand without a loss in fatigue life.

4.1.2 HUB

The hub is the supporting link between the rotor blades and the low speed shaft. It is directly connected to the shaft through a bolted interface. The

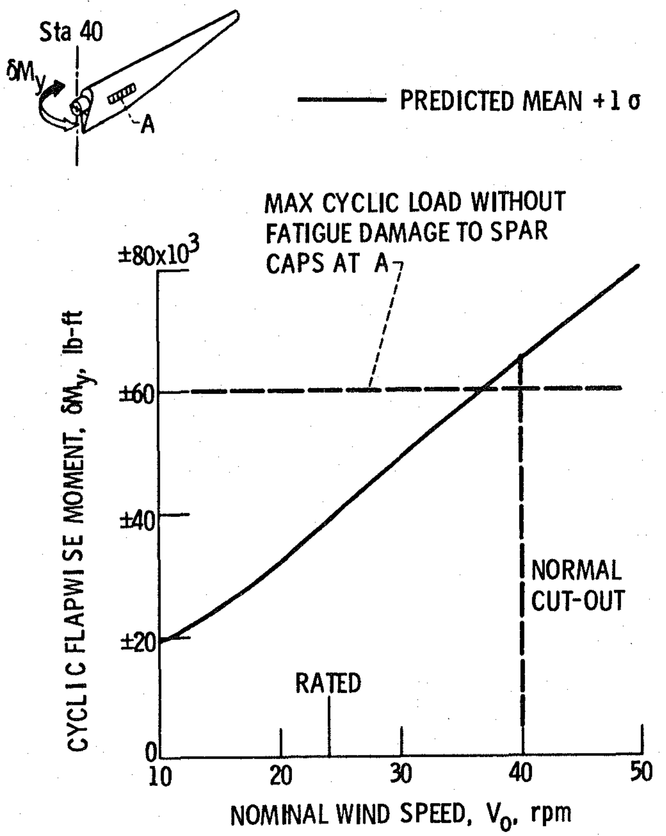

Figure 4.1.1-12. Predicted Cyclic Flapwise Bending Loads for MOD-OA Blades

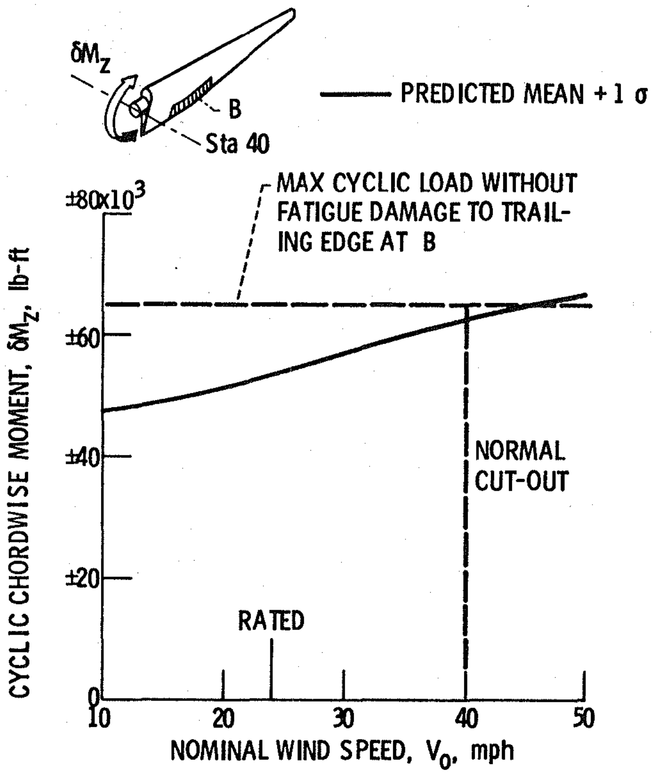

Figure 4.1.1-13. Predicted Cyclic Chordwise Bending Loads for MOD-OA Blades.

TABLE 4.1.1-2

MOD-OA BLADE LOADS

NASA "RED LINE" BENDING MOMENTS

	MAXIMUM BENDING MOMENT (ft lb)	CYCLIC BENDING MOMENT PEAK TO PEAK (ft lb)
FLAPWISE, STA. 40	200,000	130,000
CHORDWISE, STA. 40	85,000	130,000

TABLE 4.1.1-2A

MOD-OA BLADE LOADS

NASA "RED LINE" BENDING MOMENTS

	MAXIMUM BENDING MOMENT (N m)	CYCLIC BENDING MOMENT PEAK TO PEAK (N m)
FLAPWISE, STA. 40	271,000	176,000
CHORDWISE, STA. 40	115,000	176,000

hub rotates with the low speed shaft at the 40 rpm design speed. The blades are cantilevered from the hub at a 7° coning angle. The hub assembly consists of the hub forging, gears, bearings, blade spindles, and bearing housings of the pitch change mechanism. The hub also supports the actuators and the rack and pinion drives of the pitch change mechanism, all of which rotate about the centerline of the low speed shaft.

Figure 4.1.2-1 shows the hub after final machining. The unit is essentially a hollowed out forging which has been machined to mount on the low speed shaft and to accept the various components which it houses and supports. In this view, the low speed shaft interface is up and a bearing housing interface is on the right.

Figure 4.1.2-2 shows the hub assembled onto the MOD-0A WTG in the NASA LeRC facility. The blade and low speed shaft interfaces can be readily identified. The pitch change mechanism has also been assembled onto the hub at this point.

4.1.2.1 REQUIREMENTS

The configuration requirements of the hub are to interface with the low speed shaft and to contain the pitch change mechanism. The blades interface with the blade spindles which are technically part of the pitch change mechanism.

Structurally, the hub must support the blades and transmit the blade loads to the low speed shaft. The design life of the unit is 30 years. The hub must withstand the applied loads and internal and external reactions during the required lifetime without failure. The hub loadings include both the static hurricane load as well as the full range of operating loads.

Environmentally, the hub must withstand moisture without excessive corrosion and protect the moving parts of the pitch change mechanism. The hub must also ground the rotor and pitch change mechanism to the bedplate to minimize damage from lightning strikes.

4.1.2.2 APPROACH

The MOD-0A approach was to capitalize on the MOD-0 design to produce a WTG for operation in a utility environment. During the MOD-0 program, careful consideration was given to rotor/hub type and location. For that program, the downwind fixed-axis rotor was chosen as the design for which one could have greatest confidence of success. Therefore, the MOD-0A hub is essentially identical to the MOD-0 unit which had been successfully tested when MOD-0A was finalized.

4.1.2.3 SELECTED DESIGN

The hub assembly, together with the pitch change (control) mechanism, is defined in NASA Dwg. Nos. CR758864 and CD758875, (W1015F03). The unit is shown schematically in Figure 4.1.2-3. Figure 4.1.2-1 is a photograph of the hub itself. The hub is a large, rectangular housing machined from a 4340 steel forging. The size is determined by the pitch change gears and bearings. The

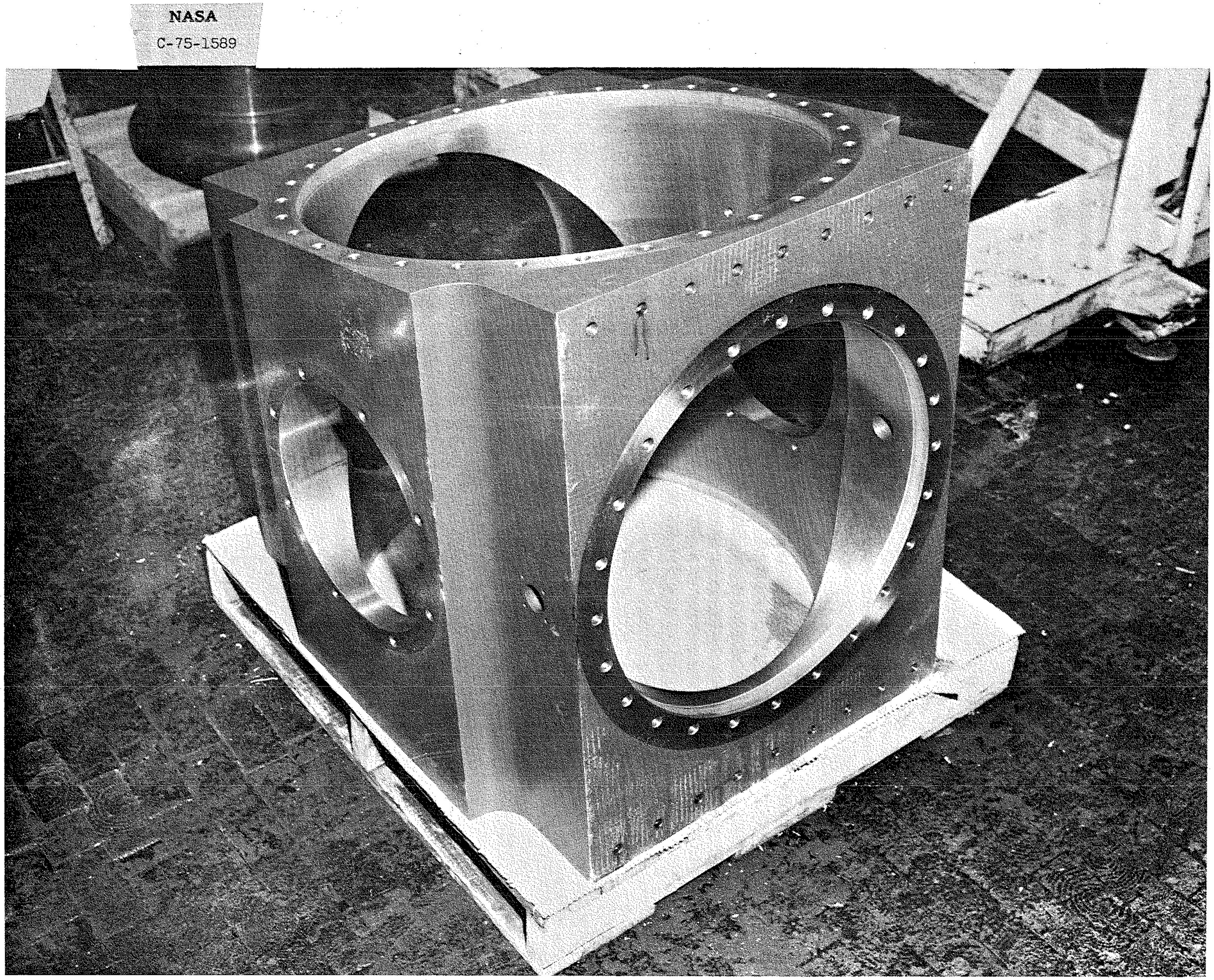

Figure 4.1.2-1. Hub After Final Machining

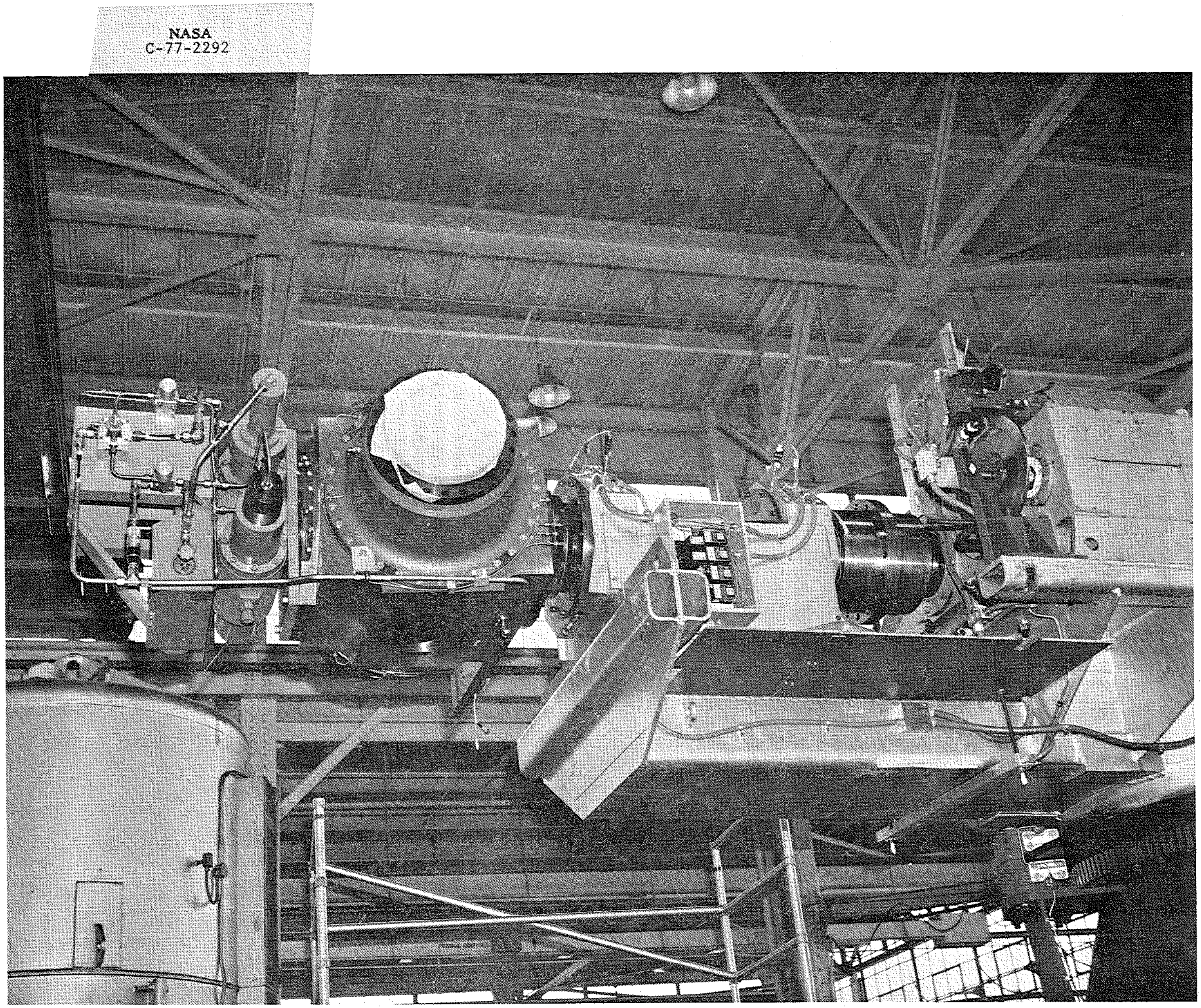

Figure 4.1.2-2. Hub and Pitch Change Mechanism After Assembly at NASA LeRC

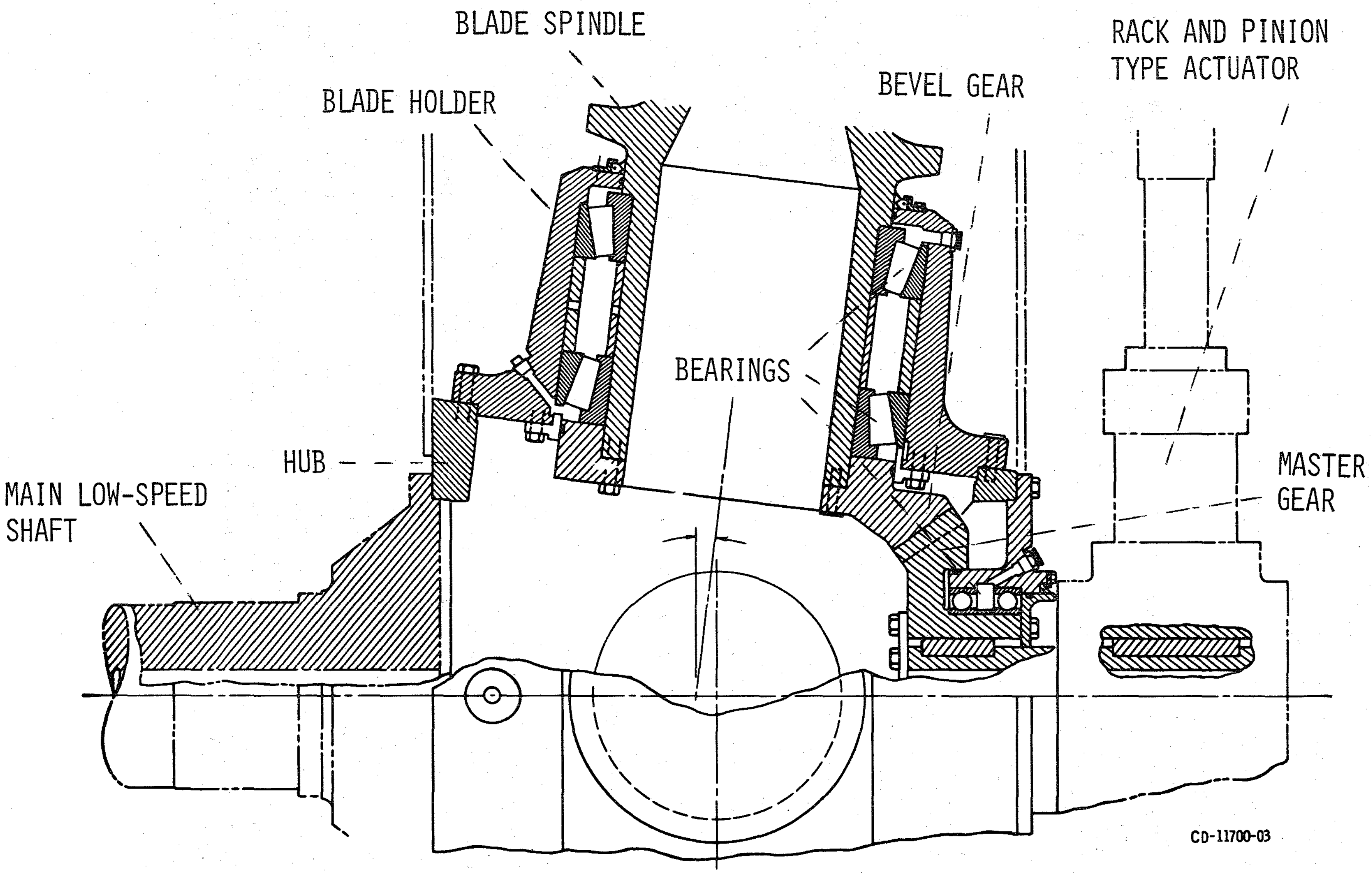

Figure 4.1.2-3. Hub and Pitch Change Assembly

bearings are commerical "off-the-shelf" items and are about as small as practical for the loads and design life.

4.1.2.4 SUPPORTING ANALYTICAL RESULTS

A stress analysis of the hub forging was performed. The finite element analysis of the hub resulted in a maximum tension plus bending stress of less than 30,000 psi (207 MPa), well below the 120,000 psi (827 MPa) yield of 4340 steel. An analysis of the blade spindle bearing housing was also performed. The effective tensile plus bending stress was well below 50,000 psi (345 MPa). It was concluded that the hub and hub components are generally overdesigned structurally.

4.1.3 PITCH CHANGE MECHANISM AND HYDRAULIC SYSTEM

The method chosen to control the electrical power output and rotational speed of the MOD-OA blades during startup, normal operation, and shutdown was to change the pitch of the blades. The rate at which the pitch must change depends on wind conditions and the resisting load of the electric generator. When changes in load and wind speed are slow, pitch is changed slowly. When the wind is gusting or when a load failure occurs, pitch is changed rapidly to prevent overspeeding the rotor which could damage the blades. Therefore, safe operation of the MOD-OA WTG depends on the ability of the pitch change mechanism and its hydraulic and electrical control systems to properly sense and respond to the various conditions to which the wind turbine is exposed.

When the machine is in the shutdown mode because the wind speed is below cut-in or above cut-out, each blade is feathered (pitch angle is approximately 90° negative) to reduce rotational torque. The rotor remains in this condition as long as the wind speed is outside the operating range.

When the wind speed changes from below cut-in or above cut-out to the operating range, the pitch of the blades is gradually changed to a value that will start the rotor spinning and bring it up to its operating speed of 40 rpm. Then the generator is synchronized with the network. If the wind speed is between cut-in and rated [18.3 mph (8.2 m/s) at a 30-foot (9.1 m) elevation], the blade pitch is set to 0° (full power position) and the rotor operates as a fixed pitch rotor. The electrical power output for this condition varies accordingly. When the wind speed is between rated and cut-out, the blade pitch is changed with changes in wind speed to maintain rated power and a 40 rpm rotor speed. Under gusting conditions, the blade pitch is changed quickly to adjust blade efficiency and prevent overspeeding the rotor. When the wind speed drops below cut-in or increases above cut-out, shutdown procedures are initiated and blade pitch is changed toward feather to slow down and stop the rotor. Emergency shutdown procedures are similar except that the pitch change rate must be high enough to prevent overspeeding of the rotor, but low enough to prevent overloading the blades. Blade pitch control is described in Section 4.7.1.

4.1.3.1 REQUIREMENTS

The prime function of the pitch change mechanism and hydraulic system is to reliably control the rotating speed and power of the rotor under all operating wind conditions, and to protect the rotor and blades from overspeed in a fail-safe manner. These functions are to be performed by a mechanism and hydraulic system which is highly reliable but also low cost, simple in design and requires only minimal maintenance in service.

The pitch change mechanism must permit the WTG to operate within the performance envelope shown in Figure 4.1.3-1. The zero degree blade pitch angle referred to in the figure is the angle at which 200 kW of electrical power is generated with the blades turning at 40 rpm in a wind of 18.3 mph (8.2 m/s) measured at 30 feet (9.1 m) elevation. The key wind speeds are as follows:

	At 30 Feet	At Hub Axis
Cut-in	6.9 mph (3.1 m/s)	9.5 mph (4.2 m/s)
Rated	18.3 mph (8.2 m/s)	22.4 mph (10.0 m/s)
Cut-Out	34.2 mph (15.3 m/s)	40.0 mph (17.9 m/s)
Maximum Design	125.0 mph (55.9 m/s)	150.0 mph (67.1 m/s)

A detailed description of pitch control operations is given in Section 4.7 of this report.

Additional requirements for the design of the Pitch Change Mechanism and Hydraulic System are as follows:

(1)	Blade Weight	2000 lb. (0.9 kg) each
(2)	Max Feather Torque Req'd.	14,000 ft. lb. (19,000 Nm), each blade
(3)	Max Continuous Blade Pitch Rate	2°/Sec
(4)	Max Instantaneous Pitch Rate	5°/Sec
(5)	Max Hydraulic Pressure (Low Maintenance)	2200 psi (15 MPa)
(6)	Pitch Change Resolution	<2°
(7)	Max Pitch Rate (Emergency Feather Condition)	8°/sec
(8)	Provide a backup means to feather blades in event of hydraulic system failure.	

4.1.3.2 DESIGN APPROACH

The approach used to arrive at the final design of the pitch change mechanism for the MOD-OA machines was to select a concept that had been used successfully and to modify and scale up the sizes as required to meet the requirements of MOD-OA. The aircraft industry has used a mechanism for adjusting the pitch of propeller blades for many years. It is this basic mechanism that was selected for use on the MOD-OA machines.

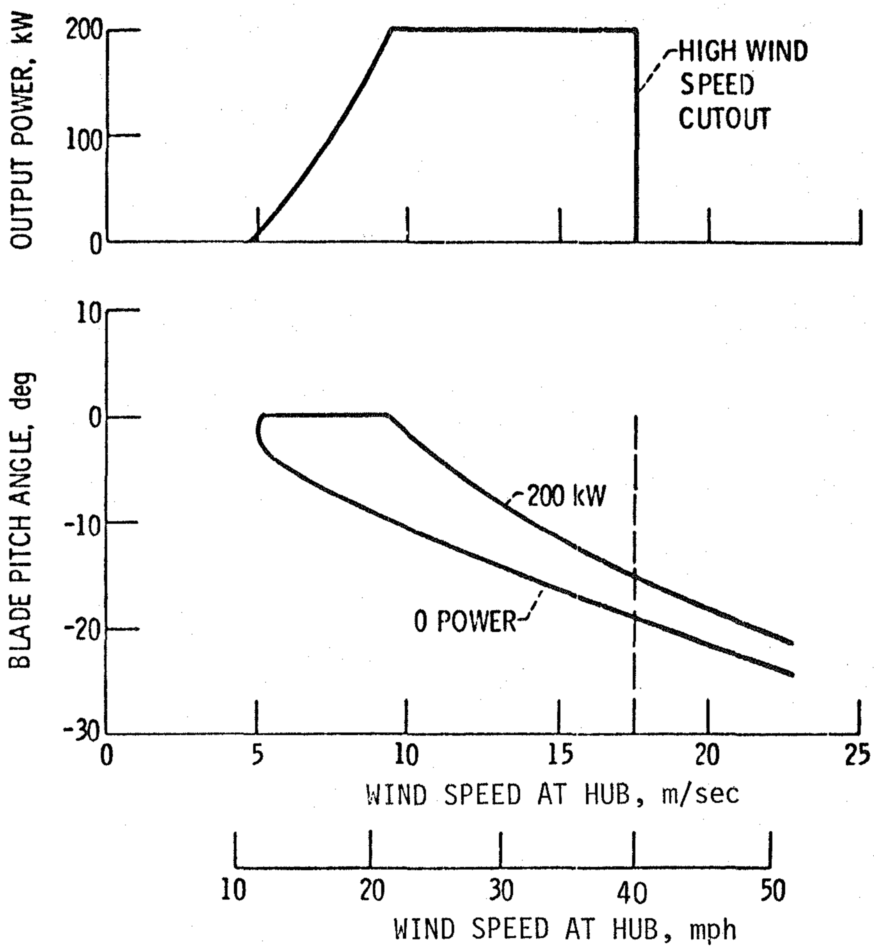

Figure 4.1.3-1. Operational Requirements of Pitch Change Mechanism

To satisfy the fail-safe feature, that is, that the blades must be turned to the feathered position if hydraulic or electric power fails, springs were considered. However, when calculations were made to determine the size of springs required, it became apparent that the large size of the springs was a burden in design and would interfere with access for maintenance during the lifetime of the machine. For this reason, a bottled gas activated cylinder was chosen to satisfy the fail-safe requirement of feathering the blades in the event of a power failure.

Blade fluttering can be a problem if the pitch change hardware does not have the capability of preventing it. Therefore, in formulating the design of the pitch change mechanism and hydraulic system, it was decided to strive for a no-backlash system having more strength than what is normally required in order to gain in rigidity and thereby prevent fluttering.

4.1.3.3 SELECTED DESIGN

The design selected for the MOD-0A pitch change mechanism is shown on NASA Dwg. Nos. CR758864 and CD758875 through CF758874 (W1015F03 through 1015F12). The hydraulic system is described on NASA Dwg. Nos. CF758921 through CF758929 and CP758929 (W1015F52 through 1015F58). Figure 4.1.3-2 shows the major components of the system after they have been assembled on the downwind side of the rotor hub. The two rack-and-pinion actuators can be seen side by side just above the mounting plate that interfaces with the hub. Above the actuators is the gas type accumulator, valving, and piping needed for the hydraulic system.

The major components of the pitch change mechanism and hydraulic system are the following:

- Gearing internal to the hub for pitching the blades.
- Hydraulic actuator assembly.
- Control valve panel assembly.
- Hydraulic pump and reservoir assembly.
- Oil cooler.

These components are described below.

The gears that are internal to the hub are shown in Figure 4.1.3-3. Each of the two blades is attached to its own bevel gear that is located inside of the rotor hub. These two bevel gears are positioned to mesh with a third bevel gear that is attached to one end of a driving shaft. A spur gear is attached to the other end of the shaft and meshes with two gear jacks that are internal with and driven by the pistons moving within the hydraulic cylinders. The pitch angle of the blades therefore is determined by the position of the pistons which is controlled by the hydraulic pressure in the cylinders. Since the blades are swept downwind at a seven degree cone angle, the bevel gears are not cut at a standard 45 degree angle, but at a 41.5 degree angle. Adjustments are made to the mechanism after assembly to minimize or eliminate the backlash that would normally exist in such a gear train.

The hydraulic actuator assembly consists of two, 6 in. (15.2 cm) diameter hydraulic cylinders, a 3 in. (7.6 cm) diameter gas cylinder, a gas filled

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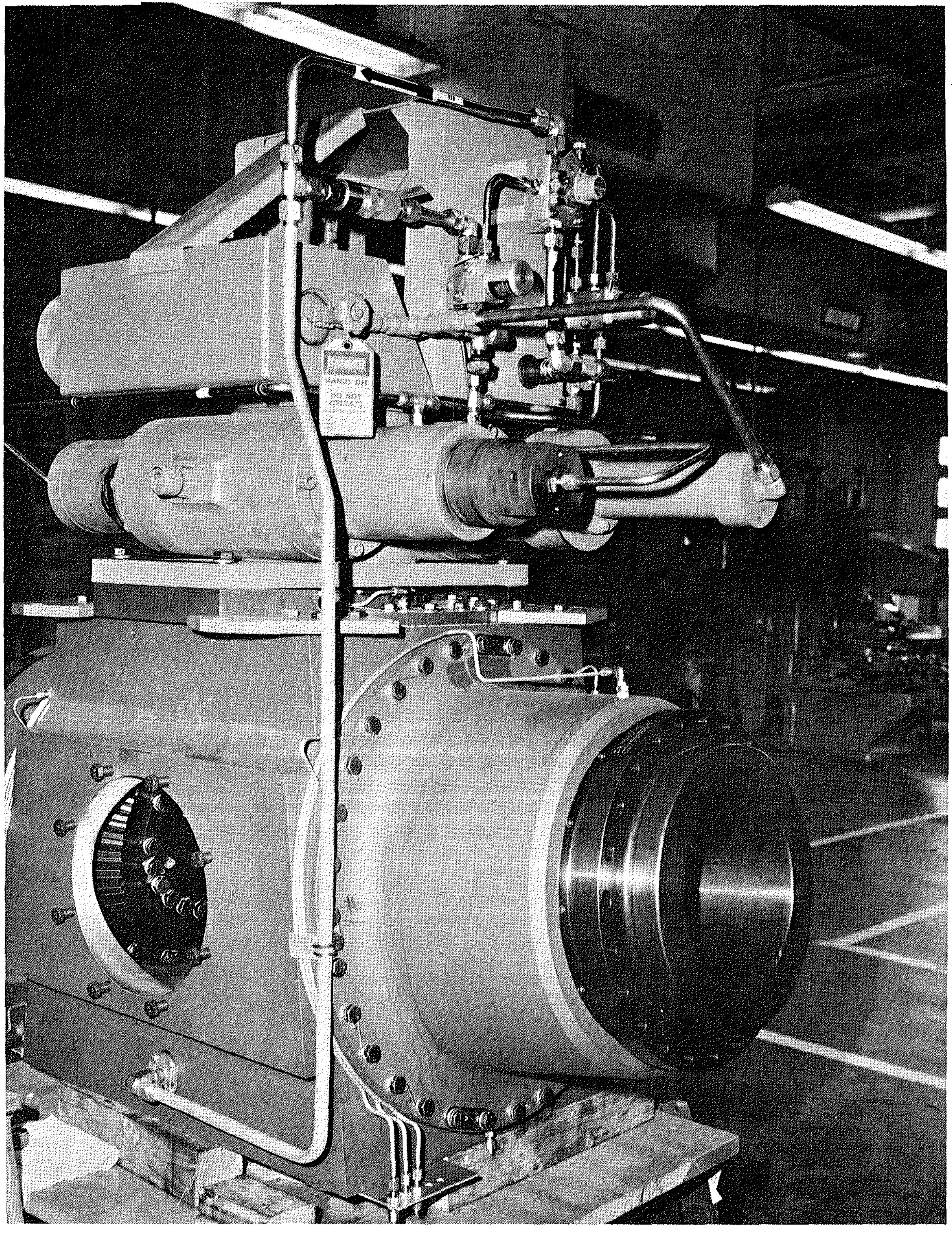


Figure 4.1.3-2. Pitch Change Mechanism Mounted on Hub

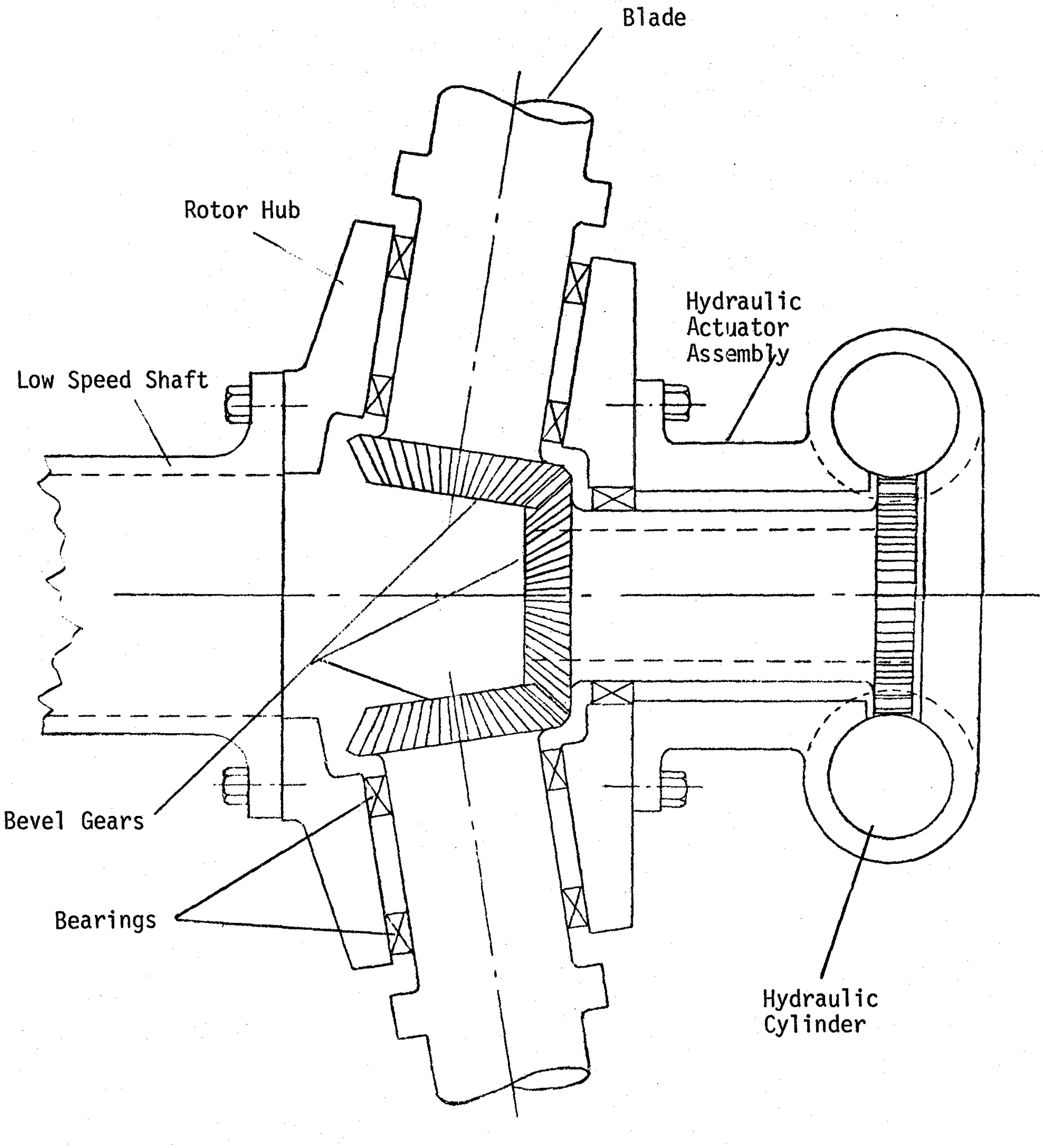


Figure 4.1.3-3. Pitch Change Mechanism (Simplified)

accumulator, an internal rack and pinion mechanism, an output shaft and the piping, fitting, and structure necessary to complete the assembly. The cylinders are mounted side by side with centers 12.5 in. (31.8 cm) apart. They are designed to operate at pressures up to 3000 psi (21 MPa) and provide sufficient stroke to rotate the output shaft through 125 degrees. The output torque capability is 600,000 inch-pounds (67800 Nm) at 3000 psi (21 MPa) pressure. The three inch (7.62 cm) gas cylinder is mounted in-line with one of the hydraulic cylinders. Its purpose is to provide the rotation required to feather the blades in the event that an electrical or hydraulic failure disables the hydraulic cylinders. The gas cylinder can supply a maximum of 39,600 inch-pounds (4500 Nm) of torque. The accumulator that is part of the hydraulic actuator assembly has a volume of 2100 cubic inches (0.034 m^3) and operates at 950 psig (6.5 MPa). Gaseous nitrogen is used to supply the pressure. The output shaft of the assembly is hollow and is sized to fit a 5.5 inch (14.0 cm) shaft. The hydraulic actuator assembly is self-contained and lubricated for life.

The hydraulic pump assembly consists of an accumulator, pump, hydraulic reservoir, oil cooler, blower, several valves, hydraulic tubing, and various miscellaneous components. This equipment supplies pressurized fluid to the pitch actuator located on the rotor. The hydraulic pump is physically located in the forward end of the nacelle along with the oil cooler and hydraulic pump and reservoir assembly. NASA Dwg. Nos. CF758929 and CP758929 (W1015F58) describe this hydraulic system schematically.

A rotating hydraulic union (seal) is needed to permit transfer of hydraulic fluid from the pitch control system pump, which is stationary, to the hydraulic actuators, which rotate with the blades. This seal assembly is located forward of the speed increaser and is in-line with the low speed shaft. Figure 4.1.3-4 shows this rotating hydraulic union after installation. It is sometimes referred to as a Deublin coupling since it is manufactured by the Deublin Company.

4.2 DRIVE TRAIN

4.2.1 LOW SPEED SHAFT, BEARINGS AND COUPLING

The low speed shaft of the MOD-OA is the shaft that turns with the rotor blades at 40 rpm during normal operation. It is supported by two large bearings and coupled to the input shaft of the speed increaser. The two bearings also support the hub and blades of the machine since the blades are attached to the hub and the hub attached to the low speed shaft. The general arrangement of components covered in this section is shown in the sketch on page 94.

4.2.1.1 REQUIREMENTS

The low speed shaft and couplings must transmit the torque generated by the wind driven blades, from the rotor hub to the input shaft of the speed increaser (gear box). Under rated conditions at 200 kW electrical power output from the generator, the torque required is approximately 48,000 ft.lb (6.5×10^4 Nm). The exact value depends on the operating efficiency of the

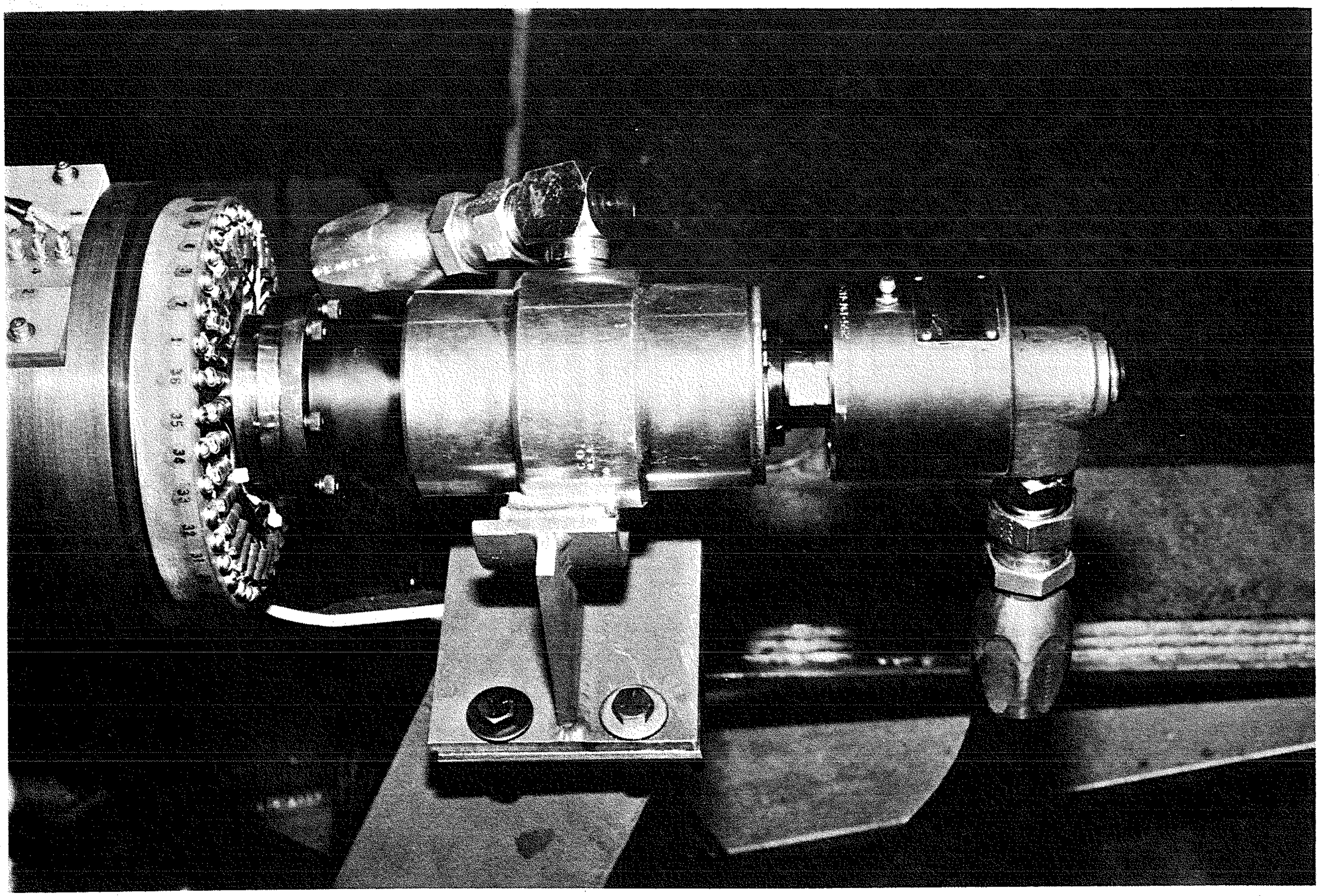
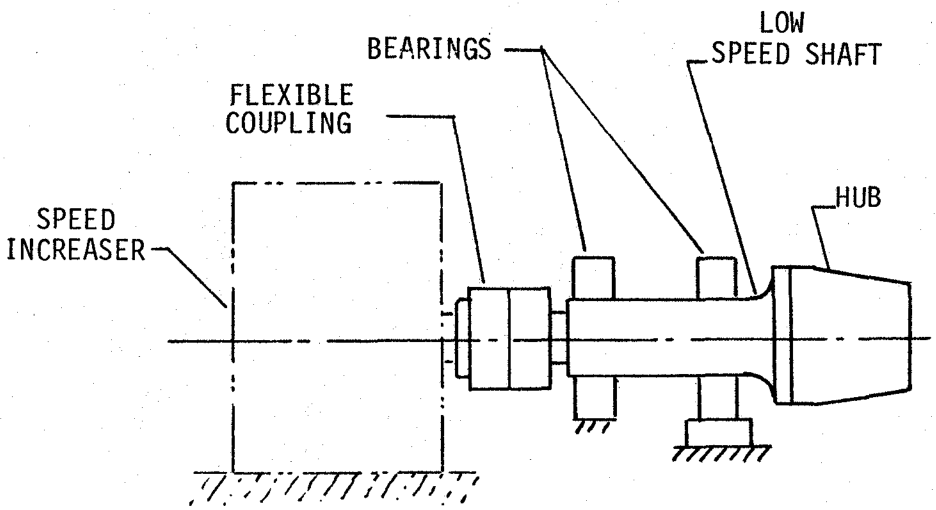


Figure 4.1.3-4. Pitch Hydraulic System Rotating Hydraulic Union

generator and speed increaser and the losses in miscellaneous components such as the shaft bearings.



In addition, the low speed shaft must provide complete support for the rotor hub and blades. Maximum critical loads have been established for the low speed shaft running at 40 rpm in a 24 mph (10.7 m/s) wind as follows:

Case	Load	Value
Yawing at 1/6 rpm	Maximum Bending	135,000 ft-lbs.(1.8 x 10^5 Nm)
Fatigue at rated conditions	Shear	4,100 lbs.(18,230 N)(N $\geq 10^7$)
" " "	Axial	7,500 lbs.(33,400 N)
" " "	Bending	54,300 ft-lbs.(73,600 Nm)
" " "	Torque	48,000 ft-lbs.(65,100 Nm)

The low speed shaft is supported by two large bearings whose housings are supported by the bedplate. The bending moment is most critical and is plotted in Figure 4.2.1-1 as a function of wind speed.

4.2.1.2 DESIGN APPROACH

In formulating the design of the low speed shaft and associated bearings and couplings, it was decided to use the basic configuration developed for the MOD-0 machine. Size increases were considered and shape modifications were made because of the higher power rating of the MOD-0A machine and because of the operational data collected on the MOD-0 machine. The fillet radius near

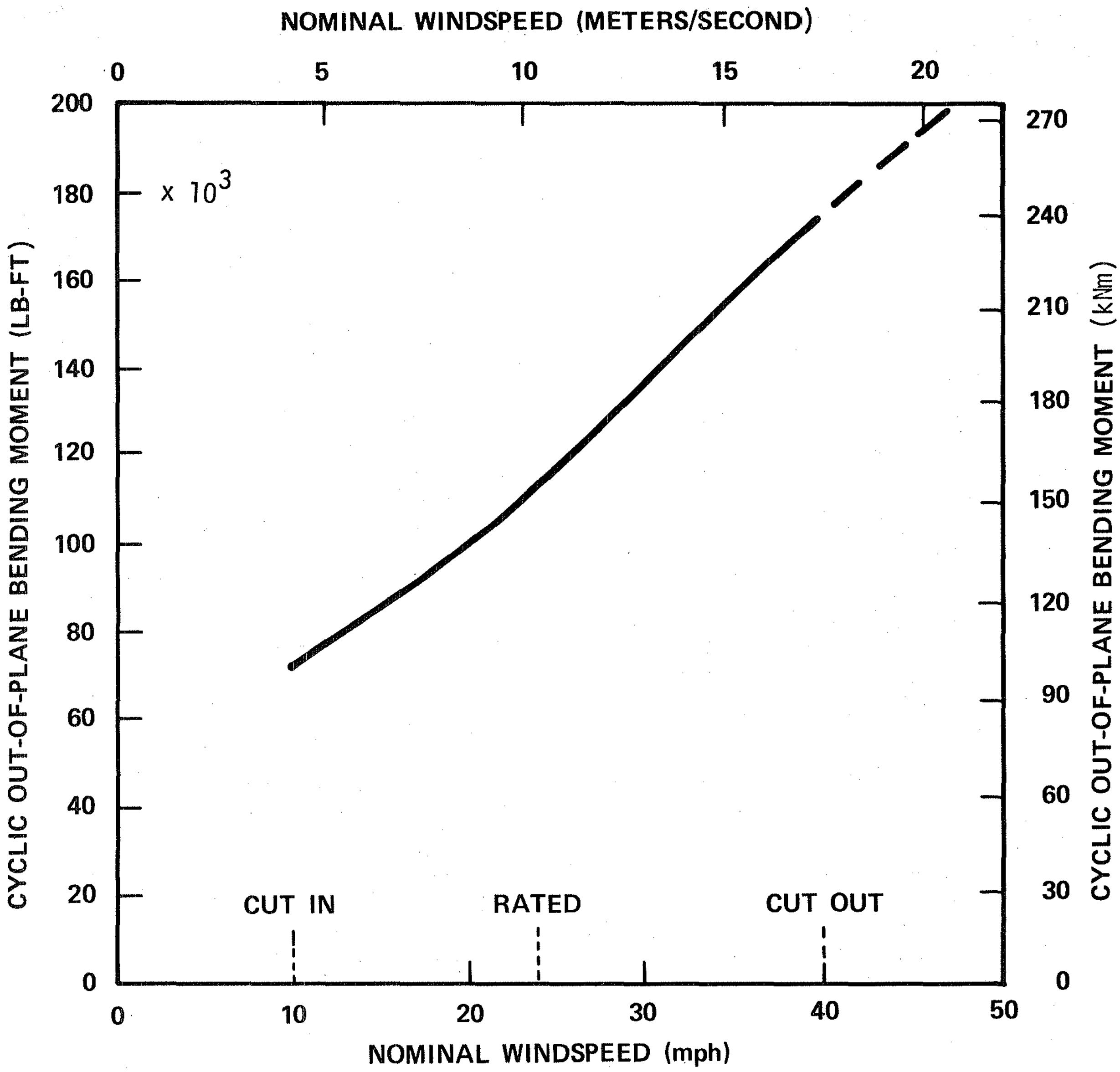


Figure 4.2.1-1. Cyclic Bending Moment on MOD-0A Low Speed Shaft (Calculated)

the hub end of the low speed shaft was enlarged to increase the margin of safety. The shaft was sized to fit commercial bearings. The ends were designed to interface properly with the hub and a commercial coupling that connects the shaft to the speed increaser input shaft. Thrust loads are reacted through the bearings and their housings instead of the speed increaser shaft.

Fatigue life of the components was considered in design. Strain gages are attached to critical stress regions of the shaft in order to monitor stress levels and thereby better understand the actual condition of the shaft during the lifetime of the machine.

4.2.1.3 SELECTED DESIGN

The designs selected for the low speed shaft, bearings and couplings are described on various drawings as follows:

Assembly	CR758862 and CR758863
Bearing Adjustment	CR758864 and CD758875
Main Drive Shaft	CF758890
Hub Assembly	CR758864 and CD758875
Bearings	Torrington No. 260 SD 32
Coupling	Falk No. 1070G
Miscellaneous Parts	CF758889

Figure 4.2.1-2 is a photograph of the selected design after the hardware was assembled in the shop. The downwind bearing housing (on the left in the photo) was designed to react vertical and side loads on the shaft and also to react axial loads originating in the blades. The other bearing housing reacts vertical and side loads only. Each bearing housing contains a self aligning spherical roller bearing. Under dynamic misalignment conditions, the spherical type bearing permits internal alignment within the bearing as it rotates. Full bearing capacity is realized with as much as 1.5 degrees of misalignment. The advantage of using a bearing of this type is that bearing races need not be carefully positioned on the supporting structure, and that often times, weldments can be used in lieu of machined and bolted assemblies. Thrust loads can be carried by such a bearing because of the spherical surfaces of the races. The dynamic capacity of each bearing is 530,000 pounds (2.36×10^6 N) based on a minimum life of one million revolutions at speeds less than 810 rpm.

The low speed shaft is shown in Figure 4.2.1-3 as it appears after having strain gages applied to the areas of critical stress. These gages stay in place and are used to monitor strain levels during operation of the machine. The shaft is approximately ten inches (25.4 cm) in diameter and five feet (1.5 m) long. The downwind end is enlarged to form a flange for bolting to the rotor hub. For high fatigue properties, grade 4340 alloy steel is used for making the shaft.

A double engagement gear type of coupling is used to connect the upwind end of the low speed shaft to the input shaft of the speed increaser. This coupling is made with two grooved steel hubs that are keyed to their respective shafts.

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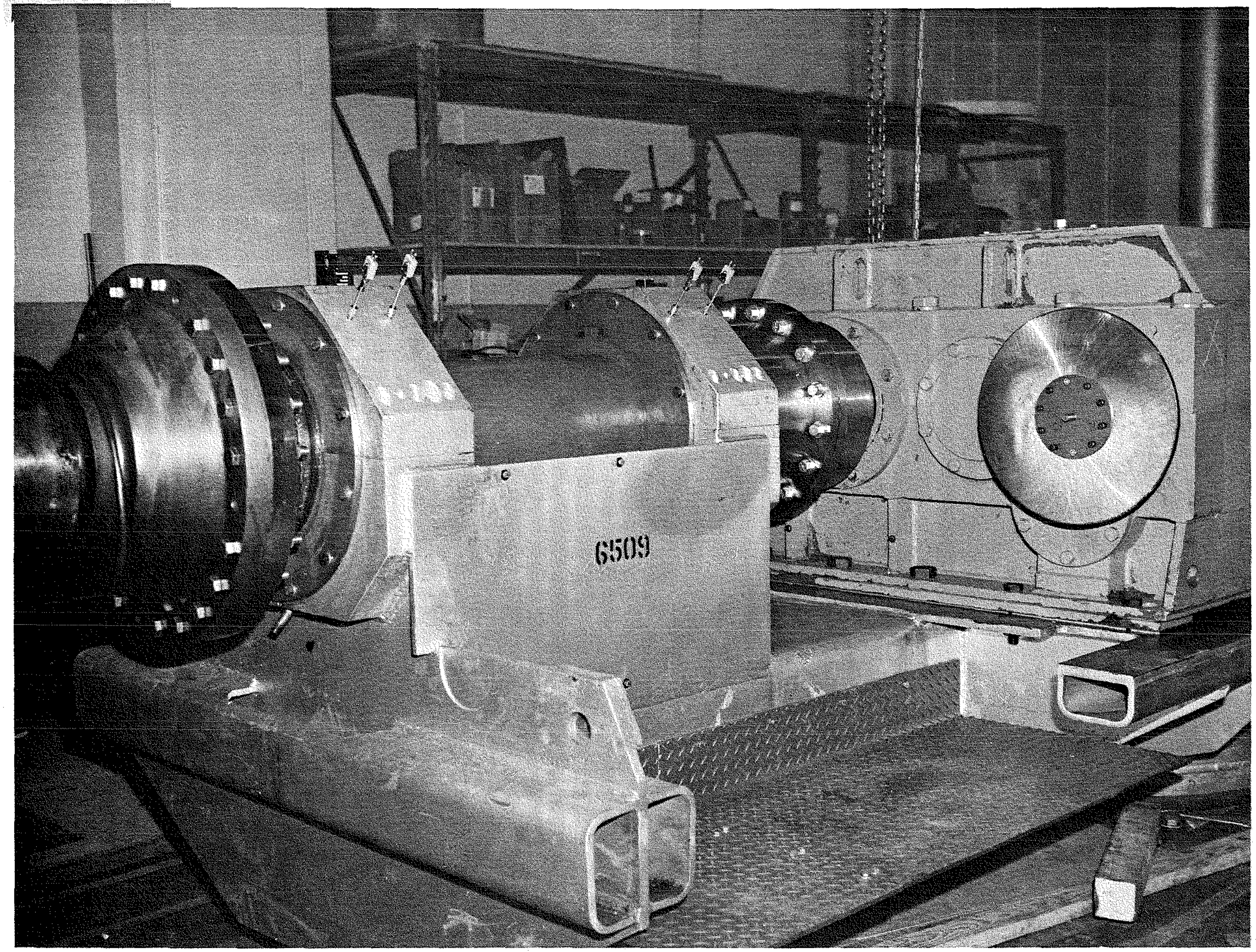

Figure 4.2.1-2. Low Speed Shaft, Bearings, Bearing Housings, and Couplings

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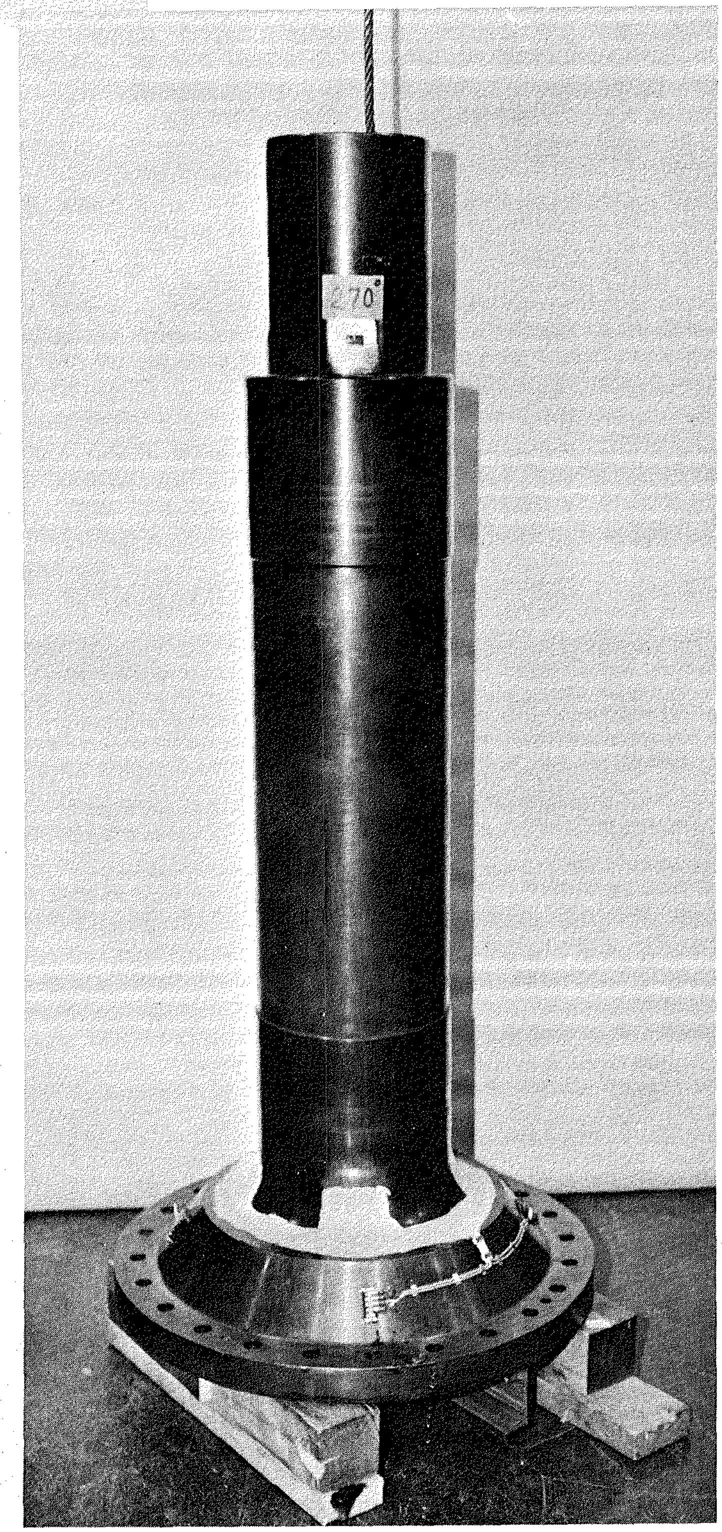

Figure 4.2.1-3. Low Speed Shaft

Each hub has external gear teeth that are crowned to accomodate misalignment. Connection between the two hubs is made by flanged members that are engaged with the gear teeth and are attached by bolts penetrating the back-to-back flanges. Elastomeric seal rings are located between the flanged members and shafts to keep foreign particles out of the working parts of the coupling. This type of coupling permits operation with some effort and angular misalignment between shafts while transmitting shaft torque.

4.2.2 SPEED INCREASER

The rotor blades of the MOD-OA are attached to the hub and are required to be rotated at a fairly low speed in order to maintain a reasonable tip speed. The generator, on the other hand, is required to rotate at a speed consistent with that used in commercial generators. Therefore, a speed increaser type transmission is needed to transfer the low speed power from the blades to the generator.

4.2.2.1 REQUIREMENTS

The speed increaser unit is required to have parallel input and output shafts. The unit is to be mounted by its base with the input and output shafts horizontal. The mounting base and mounting holes provided are to be capable of reacting all operating loads and dead loads. The unit is to be mounted inside an enclosure where it is to be protected from weather, but experience the full range of outdoor temperatures. Specific requirements for the design of the speed increaser are discussed below.

<u>Speeds and Ratio</u>

The input shaft speed is nominally 40 rpm. The output shaft speed is nominally 1800 rpm. The overall speed increase ratio of the unit is required to be 45:1. In operation, the speed of the unit is to be constant. During normal startup and shutdown (when the speeds are less than those given above), the torque is to be less than maximum.

<u>Loads and Power</u>

The speed increaser is required to be designed for full load power equal to 450 Hp (336 kW) [725,000 inch-pounds (82,000 Nm) input torque and 16,100 inch-pounds (1800 Nm) output torque]. This value includes all necessary allowances for shock and overload, as the nominal power to the driven machine is to be 360 Hp (268 kW).

The unit is required to withstand full reverse loading, while rotating in the forward direction. Such reverse loading, however, is to be infrequent and of short duration and is not to be considered in wear life and bearing life requirements.

The input and output torques are required to be applied to the shaft portions as shown on NASA Dwg. No. CD758957 (W1015F72). The downwind end of the high speed shaft is to carry a brake disk. The maximum brake torque was specified

to be 25,000 inch-pounds (2824 Nm). The unit is required to withstand this torque statically, but such braking is to be infrequent and of short duration. The shaft that carries the brake disk is to withstand a side load of 3000 pounds (13,000 N) acting in the plane indicated on NASA Dwg. No. CD758957 (W1015F72). All other shaft loads are to be applied as pure torque.

Direction of Rotation

The forward direction of rotation of the low speed shaft is required to be counter-clockwise looking upwind.

The speed increaser is to be capable of reverse rotation without damage. In service, reverse rotation is to be:

- Infrequent and of short duration.
- At reduced speed (less than 10 percent of operating speed).
- At torque levels up to full operating torque.

Temperature, Heating and Cooling

The speed increaser is required to operate in ambient temperatures from -20°F to +110°F (-29°C to 43°C) without cooling.

Cooling requirements, if any, are to be determined and specified for the design by the manufacturer.

If necessary to accommodate operation at the low end of the temperature range, an electric immersion heater is to be provided in the sump of the unit. This heater is required to have an integral thermostatic control and operate on 240 V, 60 Hz, single phase current.

The maximum acceptable temperature rise for the unit at rated speed and load is to be determined and specified for the design by the manufacturer.

Lubrication

Lubrication of the speed increaser is required to be entirely integral with the unit. The unit is to include a window or gage glass for visual inspection of proper oil level. The window or gage glass is required to be located on the side indicated on NASA Dwg. No. CD758957 (W1015F72).

Life

The gearing is required to have a design life of 35,000 hours at the following load schedule:

- 100 horsepower (74.6 kW) for 8,750 hours
- 250 horsepower (179 kW) for 12,250 hours

- 450 horsepower (336 kW) for 14,000 hours

The L-10 life of all bearings in the unit is to be 35,000 hours or greater at design speed and 450 Hp (336 kW).

Efficiency

The mechanical efficiency of the speed increaser (output power/input power) is requried to be 90 percent or greater for the following conditions of operations:

- Full design speed in the forward direction.
- Any power level from 360 Hp (268 kW) to 450 Hp (336 kW).
- Any ambient temperature from -20°F to +110°F,(-28°C to 43°C).

Dimensional and Configuration Requirements

The speed increaser is to conform to the dimensional requirements of NASA Dwg. No. CD758957 (W1015F72). The purpose of the 3.25 inch (8.2 cm) hole through the low speed shaft is to accommodate electrical and instrumentation wiring as well as high pressure hydraulic lines. The external extension of the non-driven end of the low speed shaft is to accommodate the slip ring assembly.

Instrumentation

One thermocouple is required to be installed at each of the following locations:

- Each bearing of the low speed shaft.
- Each bearing of the high speed shaft.
- Oil sump, to sense oil temperature.

The bearing thermocouple is to be installed in spring-loaded contact with the outer surface of the outer race of the bearing on the portion of the race that is most highly loaded in normal operation. All thermocouples are required to be iron-constantan type, fully jacketed, insulated junction, 1/8 inch (0.32 cm) outside diameter.

The thermocouple leads are to emerge from the gear case in the area indicated on NASA Dwg. No. CD758957 (W1015F72). The external leads are required to have a ten inch minimum length; each is to be identified and terminated with a male, standard thermocouple alloy plug.

Testing

The speed increaser is required to be shop tested at full speed and no load. The unit is to be run a minimum of two hours at full speed after the oil temperature has stablized. During the two hour test, there is to be no increase in vibration, noise level, or bearing temperature.

4.2.2.2 DESIGN APPROACH

The speed increaser used on MOD-OA was patterned after the unit designed and operated on the MOD-0 wind turbine generator. Since the MOD-0 unit ran successfully, the approach used for designing the MOD-OA speed increaser was to use the same basic design, but increase the size of the unit and hardness of the gear teeth as necessary to transmit the additional power.

4.2.2.3 SELECTED DESIGN

The design selected for the MOD-OA speed increaser is shown on NASA Dwg. No. CD758957 (W1015F72). The gearing is housed in a casing that is 34.5 inches (87.6 cm) high, 54.0 inches (137.2 cm) wide and 30.0 inches (76.2 cm) deep (axial dimension). The low speed shaft of the speed increaser operates at 40 rpm. It is 9 inches (22.9 cm) in diameter and contains a 3.0 inch (7.6 cm) central bored hole running the full length of the shaft, 43.25 inches (109.8 cm). Oil seals and bearings are located near each end of the low speed shaft.

The high speed shaft of the speed increaser operates at 1800 rpm. This shaft has 3.0 inch (7.6 cm) diameter ends for mating with connecting components. Oil seals and bearings are located near each end of the high speed shaft. Both the low speed and high speed shafts, and also the second shaft (an intermediate shaft), are located 18.5 inches (47.0 cm) above the base of the speed increaser assembly. The second shaft is 6.0 inches (15.2 cm) in diameter and operates at 153 rpm. It is supported by bearings at each end and held within the casing by a retaining plate at each end. An additional intermediate shaft, or third shaft is 4.5 inches (11.4 cm) in diameter and located about 10 inches (25.4 cm)above the base. This shaft is totally enclosed within the speed increaser casing.

Helical gears are used throughout the unit for quiet operation and to maximize power transmission capability. The gear train consists of six gears, arranged in pairs as follows:

Shaft	Pitch Dia. (Inches)	Pitch Dia. (cm)	No. of Teeth
first/second	26.966/7.034	68.494/17,866	92/24
second/third	19.099/4.901	48.511/12,448	113/29
third/high speed	13.532/4.468	34.371/11.349	106/35

The speed increaser has a turning ratio of 45.24 to 1 and is rated at 450 horsepower (336 kW) at 1800 rpm. For lubrication, 35 gallons (132 liters) of type AGMA No. 4 oil were initially contained within the unit. During the drive train run-in tests on the speed increaser (see Section 5.1.1 below), the oil level was lowered and the type of oil was changed to a Mobil SHC 629 synthetic. Thus, 26 gallons (98.4 liters) of synthetic oil were used for lubrication. The unit was designed to operate with an oil temperature between 50°F and 180°F (10°C and 82.2°C). A Chromalox heating element, in conjunction with a Chromalox thermostat, was included in the design for the purpose of maintaining oil temperature above the 50°F (10°C) minimum. Actually, NASA LeRC found that they did not need this heater, especially with the use of synthetic oil in the speed increaser. The temperature of both the input and output

bearings is monitored by thermocouples that are spring loaded against the outer race of both bearings. The approximate weight of the speed increaser unit is 5500 pounds (2500 Kg.).

Figure 4.2.2-1 presents a photograph of the speed increaser unit as it appears during shop assembly of the MOD-OA wind turbine generator. Manufacturer of the speed increaser was Horsburgh & Scott Company, Cleveland, Ohio.

4.2.2.4 ANALYTICAL RESULTS

Variations in power output of the WTG can occur if wind speed fluctuations are too rapid to be matched by the blade pitch change mechanism. Also, blade passage through the tower blockage region can create periodic dynamic input disturbances. Since these disturbances can travel through the speed increaser and other components of the drive train, the characteristics of the speed increaser were required to be known before a complete analysis of the dynamic response of the drive train could be completed.

The speed increaser dynamic analysis results indicated that the torsional stiffness of the unit from input shaft to output shaft was 3.06×10^8 in. lb./radian(3.46×10^7 Nm/radian). The mass moment of inertia of the gears and shafts was calculated to be 4456 in-lb-sec^2 (503.4 N-m-sec^2). If the flexible coupling is included, the value becomes 4610 in-lb-sec^2 (520.8 N-m-sec^2).

4.2.3 HIGH SPEED SHAFT, BEARINGS, COUPLINGS, BELT DRIVE, AND FLUID COUPLING

The high speed shaft is the shaft that turns with the output shaft of the speed increaser at 1800 rpm during normal operation. This shaft and the other components covered in this section transmit torque from the output shaft of the speed increaser to the shaft of the generator. Figure 4.2.3-1 shows the arrangement of components.

4.2.3.1 REQUIREMENTS

The main requirement for the high speed shaft and associated components is to transmit up to 300 horsepower (223.7 kW) from the output shaft of the speed increaser to the generator shaft. Turning speed for rated conditions is 1800 rpm. In order to give options to operate the rotor and blades at steady state speeds other than 40 rpm, it was required that the high speed shaft arrangement be capable of being set at four additional speed ratios. Two ratios allow the blades to turn faster than 40 rpm and two, slower.

An additional requirement is to provide some amount of torsional damping in the drive train. Damping is required to reduce power fluctuations when wind speed variations are too high in frequency for automatic compensation by the blade pitch control mechanism.

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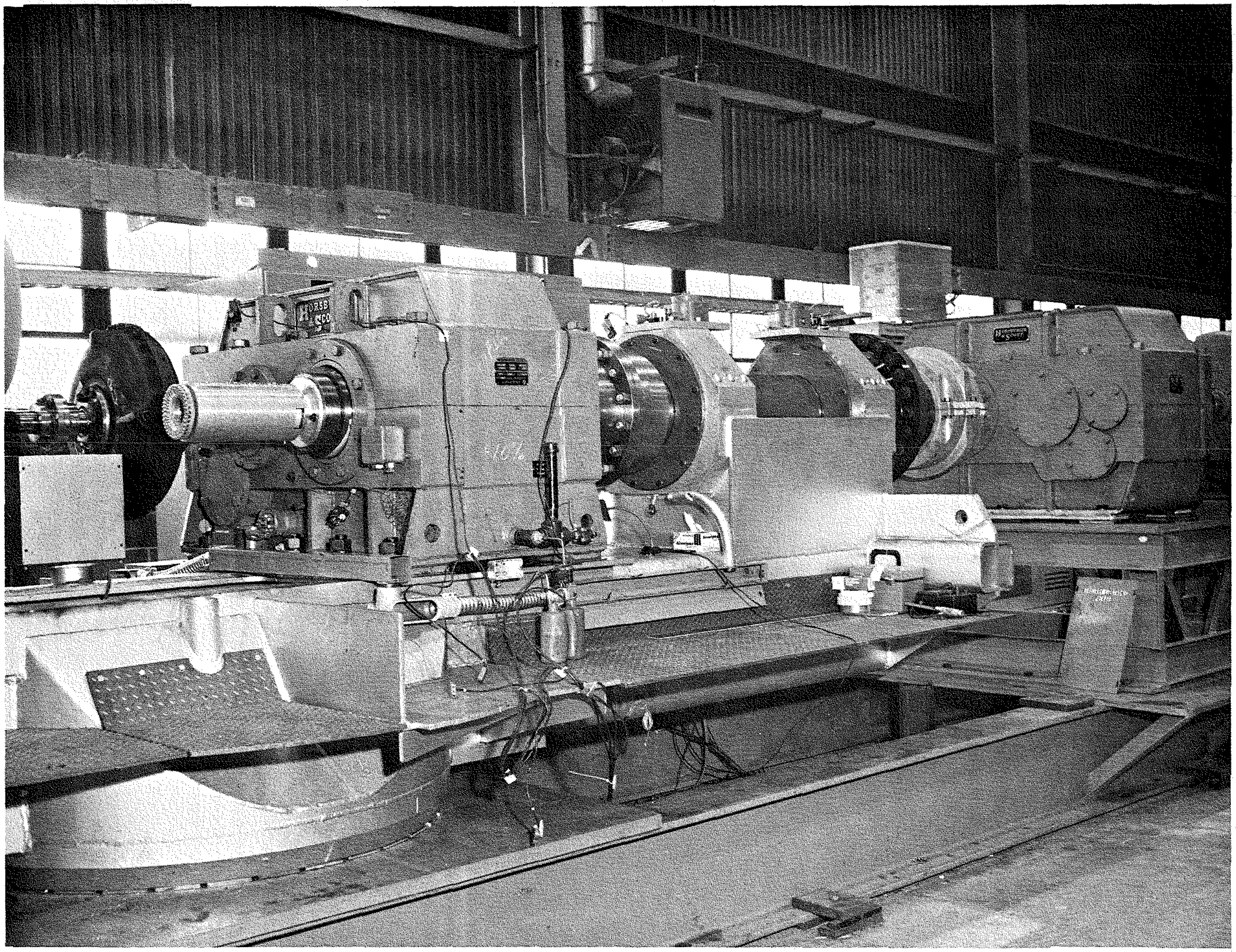

Figure 4.2.2-1. Speed Increaser Installed

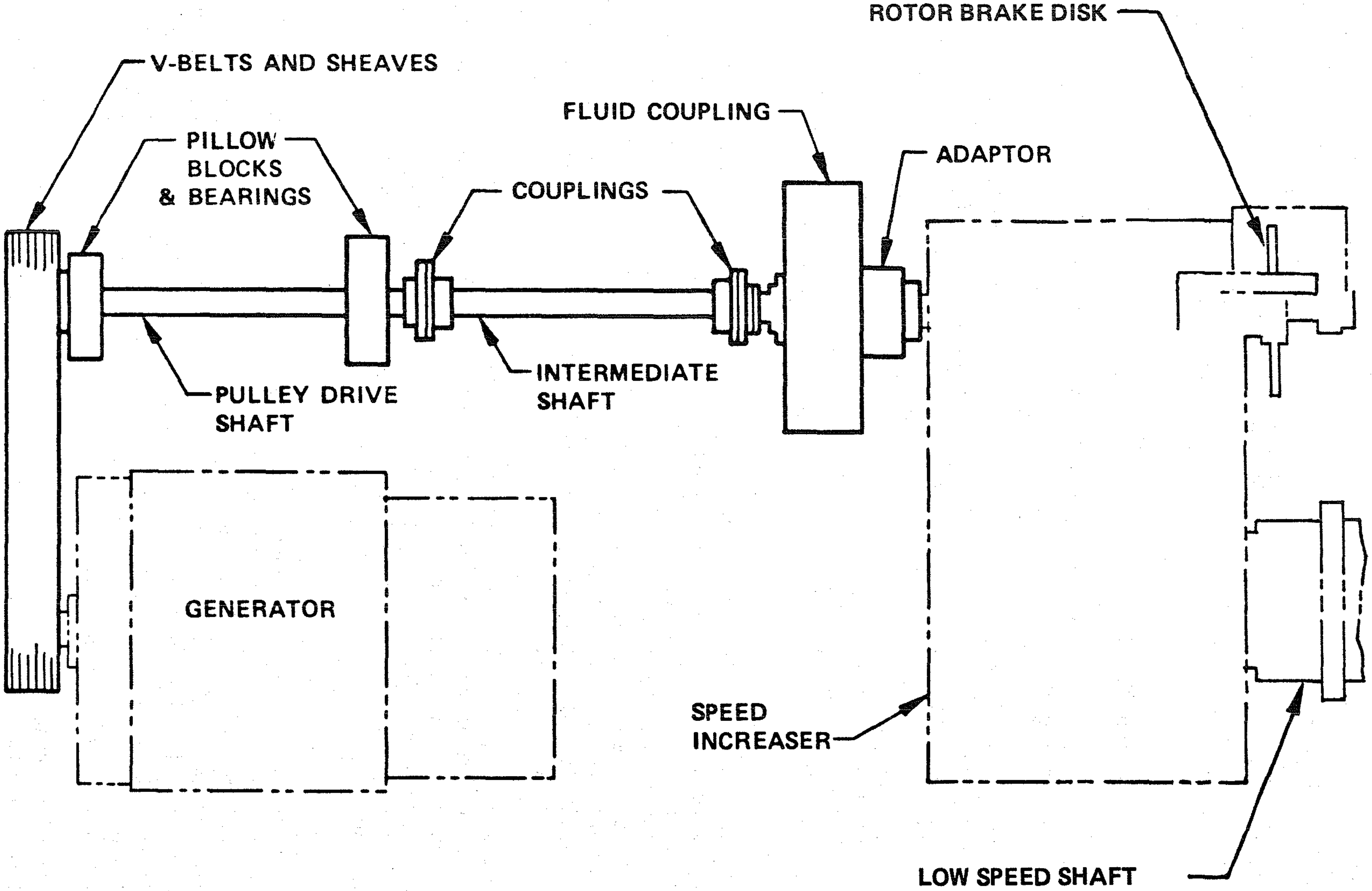

Figure 4.2.3-1. Arrangement of High Speed Shaft Components

4.2.3.2 DESIGN APPROACH

The design approach was to use an arrangement of components that would permit V-belts to be used and changed if necessary to attain different turning speed ratios. A fluid coupling was used in the drive train to provide the torsional damping required.

4.2.3.3 SELECTED DESIGN

The design selected for the high speed shaft components is described on the following drawings:

Assembly of Parts	CR758862 and CR758863
Adaptor	CC759000 and CC760487
Intermediate Shaft.	CD758999
Fluid Coupling	Am. Std. SS-550
Couplings	Zurn FS-102
Pulley Drive Shaft	CD758895
Pillow Block Assembly. . . .	Torrington FSAF-22517A
Pulley Sheaves	Browning Grip Belt 10U5V132
V-Belts	Browning Grip Belt 5V1060

The fluid coupling used has a vaned impeller and a vaned runner. The runner connects to the intermediate shaft and runs at 1800 rpm. The casing is 25 inches (63.5 cm) in diameter and 13 inches (33.0 cm) in axial thickness. The input side of the coupling is bolted to a flange fitted in the output shaft of the speed increaser. The output shaft of the coupling is 2.75 inches (7.0 cm) in diameter and is coupled to the intermediate shaft. The fluid coupling is used to reduce the magnitude of the oscillations in the drive train that are transmitted to the generator.[44]

During startup, the impeller acts as a centrifugal pump, creating an outward-flowing stream of oil. This oil crosses the narrow gap between the impeller and runner, causing the runner to act as a turbine. Here the oil gives up its kinetic energy to the runner and slowly returns to the impeller. There are no mechanical connections between the input and output of the fluid coupling. The fluid coupling is shown after being coupled to the speed increaser in Figure 4.2.3-2.

The intermediate shaft is connected to the fluid coupling at one end and the pulley drive shaft at the other end with two separate gear type couplings. Each coupling consists of two hubs and two flanged rings. One hub is attached to each of the shafts to be coupled together. The hubs have external gears that engage with internal gears on flanged rings that are assembled and bolted face-to-face for transmitting torque across the interface. These couplings can tolerate some misalignment while operating. Structural support for the intermediate shaft is also provided by the couplings.

Pillow block assemblies provide rotational support for the pulley drive shaft as shown in Figure 4.2.3-3. A pulley sheave is attached to the end of the pulley drive shaft, as well as to the shaft of the generator. As many as ten

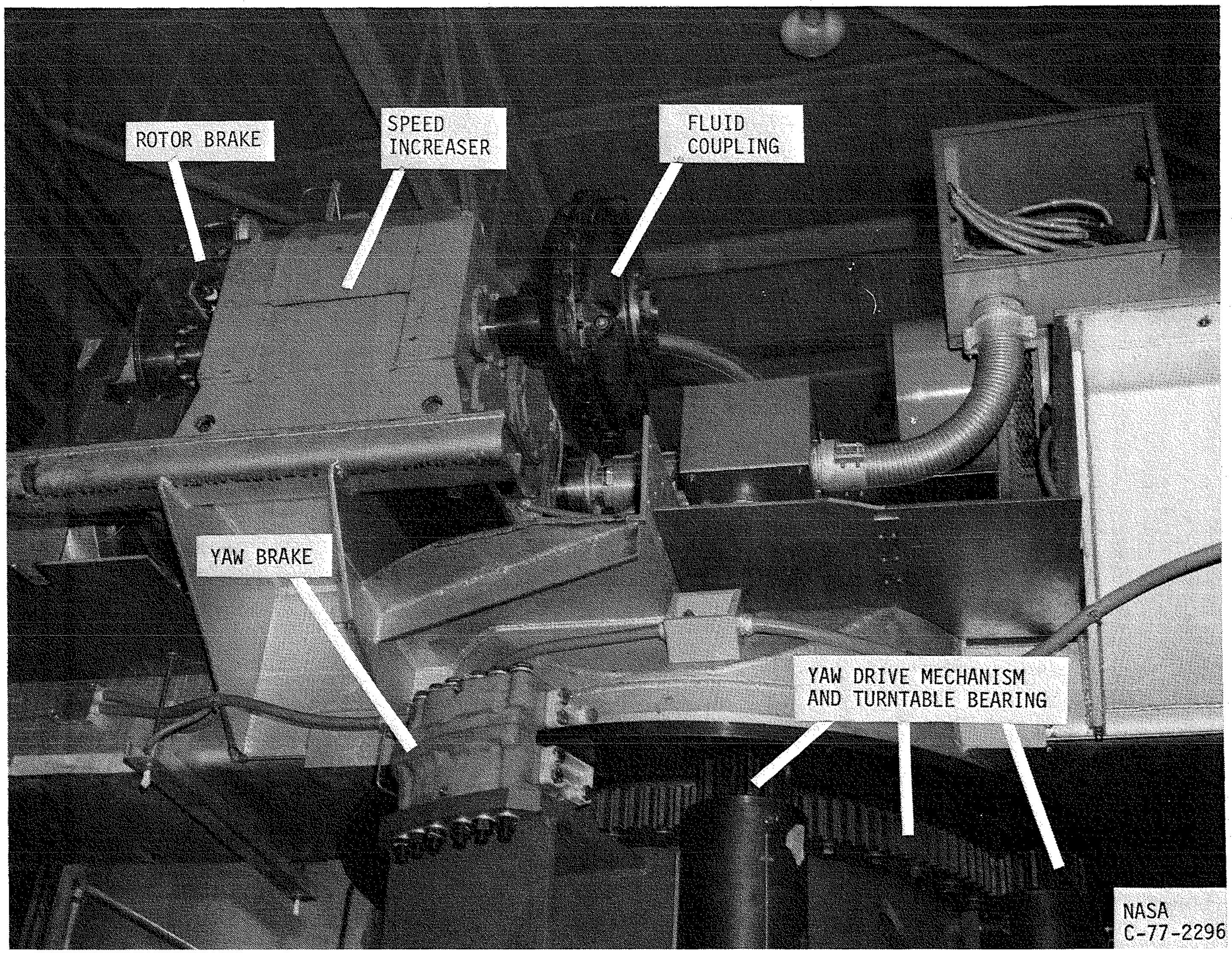

Figure 4.2.3-2. Fluid Coupling, Speed Increaser, and Rotor Brake

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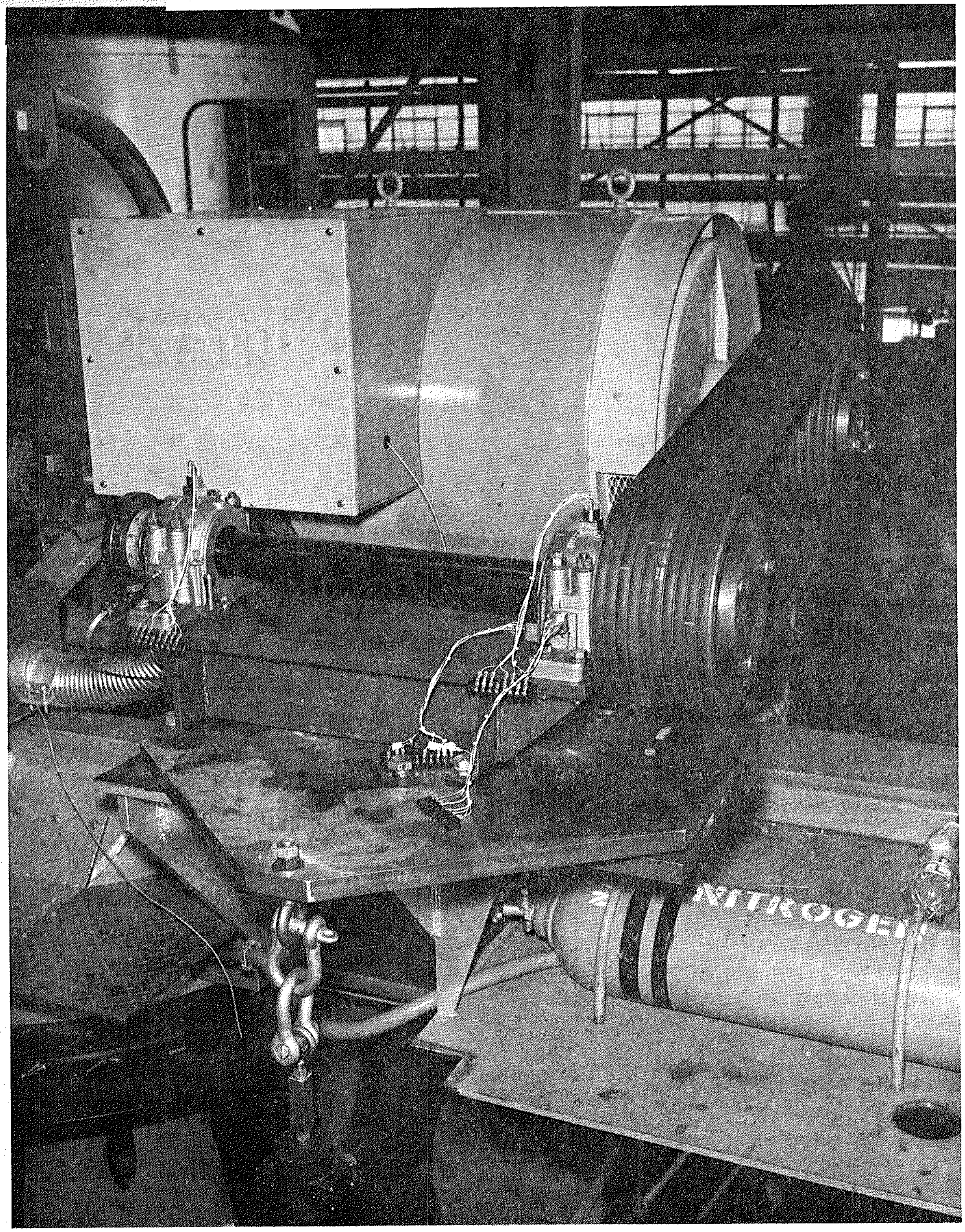


Figure 4.2.3-3 Belt Drive for Generator (Shown During Belt Tension Test)

V-belts are used for transmitting torque from one sheave to the other and thus into the generator.

The belt drive consists of different diameter sheaves and different length belts. Three sets of sheaves and belts allow for the belt drive to be assembled in different ways. These arrangements permit the generator, the high speed shaft, and the rotor blades to be operated at the following speeds (in rpm):

Case	Generator	HS Shaft	Rotor Blades
1	1800	1800	40
2	1800	1200	26-2/3
3	1800	900	20
4	1800	3600	80
5	1800	2700	60

Normal operation, however, conforms to Case 1 where the generator and high speed shaft turn at identical speeds.

4.2.3.4 ANALYTICAL RESULTS

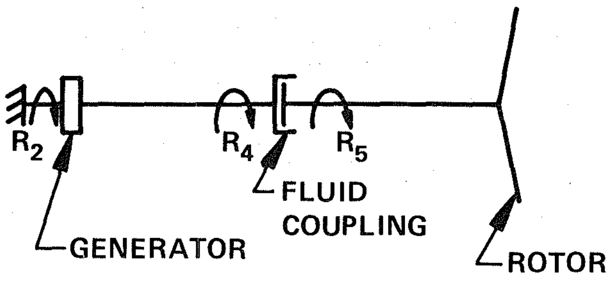
A finite element model of the MOD-0 drive train[44] was modified to include the damping provided by the fluid coupling. The model was then used to predict the effect of the amount of slip taking place at the fluid coupling on the drive train fundamental natural frequency. Also determined was the effect of slip on the relative rotation from one side of the fluid coupling to the other. The operating condition chosen for this study was 100 kW synchronized. Frequencies and modes shapes were obtained using the direct complex eigenvalue analysis of the NASTRAN computer code.

Damping is the resisting force per unit velocity on a body as it moves through a viscous medium. For a rotating system, it is torque per unit rotational velocity, or: $c = T/\delta w$, where c is the damping, T is the torque, δ is the slip and w is the rotational speed. For MOD-0 at 100 kW, T=5000 in-lb (565 Nm) and w=188.4 rad/sec (1800 rpm). Then, for example, the damping for 1 percent slip is 2654 in-lb-sec (300 N-m-sec).

The effect of slip on drive train fundamental frequency and relative rotation is shown in Figure 4.2.3-4. The location of rotations: R_2, R_4, and R_5 is indicated on the schematic of the drive train included in this figure.

As slip is increased, the drive train first mode frequency decreases until at a slip of 2.25 percent the mode disappears. In other words, the rotor and generator become dynamically uncoupled. Examining the effect of slip on relative rotation, it is seen that the rotation on the generator side of the fluid coupling decreases until at a slip of 1.3 percent, the oscillation is zero. If the slip is increased further, the generator and rotor oscillate in opposite directions.

This analysis suggested two operating conditions which might minimize power oscillations due to excitation of the fundamental drive train natural



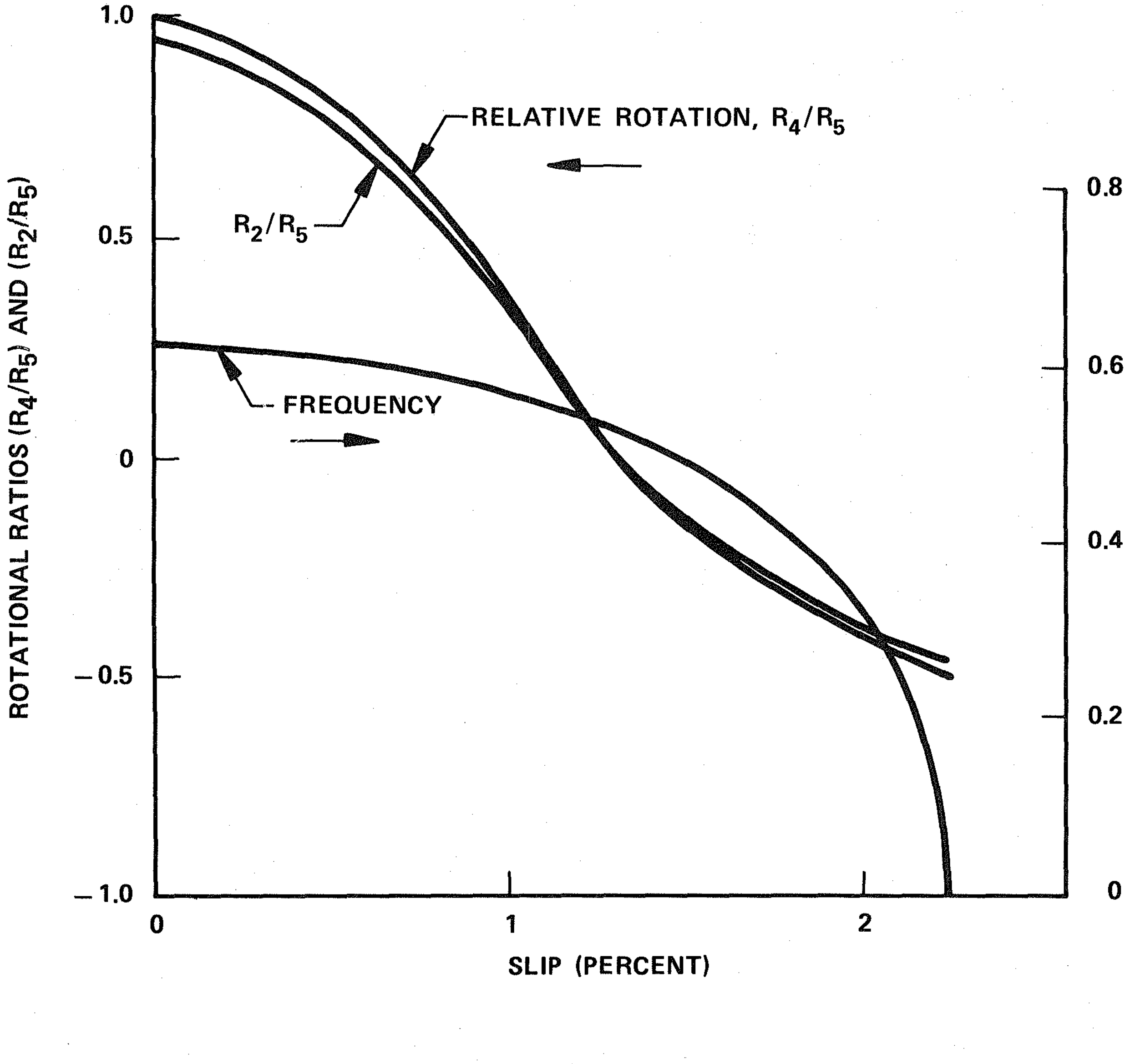


Figure 4.2.3-4. Effect of Fluid Coupling Slip on Relative Rotation and Drive Train Fundamental Frequency (100 kW, Synchronized)

frequency. The first is to operate with a slip of 2.25 percent or more to decouple the rotor and generator, and eliminate the low frequency mode. The second would be to operate at a slip of 1.3 percent so that oscillations on the rotor side of the coupling do not get transmitted to the generator. Power losses would be less operating at this lower slip condition. However, the slip at which generator oscillation vanishes varies with power generated. Therefore, from a practical point of view, it would be better to operate at the first condition with 2.25 percent slip.

4.2.4 ROTOR BRAKE

The rotor brake is a device located just downwind of the speed increaser, on the high speed shaft of the speed increaser.

4.2.4.1 REQUIREMENTS

The purpose of the rotor brake is twofold. It is required to serve as a static brake and prevent rotation of the blades during shutdown periods of the machine. It is also required to serve as a dynamic brake in an emergency case where shutdown is necessary. For safety considerations, the rotor brake must be fail-safe, i.e., on loss of power, the brakes must automatically be applied.

The brake must be capable of applying a braking torque of 25,000 in-lbs (2824 Nm) on the high speed shaft of the speed increaser.

4.2.4.2 DESIGN APPROACH

The approach used in designing the rotor brake was to locate the brake on the high speed shaft rather than the low speed shaft, since this location was a region that could be utilized for the rotor brake hardware without impacting the size of the bedplate or nacelle. Maintenance access in this area was also determined to be good.

The approach used for sizing the brake was to assume a failure in the pitch change system while wind speed was increasing, and to size the rotor brake to stop rotation of the blades in a short period of time, while not transmitting too much torque through the speed increaser gearing.

The conditions chosen for design correspond to a case that is conservative on the side of safety. This case is described as follows:

> Assume the machine to be operating at full power in a 24 mph (10.7 m/s) wind when the wind speed suddenly increases at a rate of one mph/second (0.45 m/s^2). The pitch change mechanism fails to respond and rotor speed consequently increases, driving the system out of sync in relation to the network, thus causing a no load condition on the drive train. At a rotor speed of 45 rpm, the rotor brake is applied to prevent excessive overspeed of the blades.

4.2.4.3 SELECTED DESIGN

The rotor brake selected for use on the MOD-OA machines is Model No. 9336, as manufactured by the Horton Manufacturing Company. A heavy bracket structure for mounting the brake is shown on NASA Dwg. No. CD758892 (W1015F28). Figure 4.2.3-2 shows the rotor brake as installed in the machine.

The brake uses a mild steel disk 18 inches (45.7 cm) in diameter and 0.5 inches (1.27 cm) thick. The disk is coupled to the high speed shaft of the speed increaser and rotates at 1800 rpm when the WTG is operating. Two calipers are used for retarding the motion of the disk when the brake is activated. The calipers are actuated by pressurized nitrogen that is stored on the machine in a commercial gas storage cylinder. The nitrogen supply system is completely independent from the pitch control system to make sure that a single failure cannot make both the rotor brake and pitch control systems inoperative. The pneumatic system was chosen for the rotor brake instead of a hydraulic system because of its lower cost and non-dripping characteristics. Less maintenance is expected on the pneumatic system.

4.2.4.4 ANALYTICAL RESULTS

Analysis on the dynamic braking capability of the rotor brake indicates that the brake can exert sufficient force to stop rotation of the blades in 6.3 seconds, for the conditions stated above under "Design Approach". For this case, the brake exerts 25,000 in-lbs (2824 Nm) of torque on the high speed shaft. This produces power and torque values in the speed increaser of 805 horsepower (600 kW) and 95,000 ft-lbs (10,700 Nm), respectively.

Heating of the brake disk during the shutdown case described is expected to be significant, but not severe enough to prevent proper braking action to take place.

4.3 NACELLE EQUIPMENT

The nacelle equipment is the equipment mounted on top of the tower for the purpose of supporting and housing the power generating equipment. It includes the fiberglass nacelle, the structural bedplate, the yaw bearing support cone and the mounting frame.

4.3.1. REQUIREMENTS

The nacelle equipment is required to provide support for the power generating equipment which weighs approximately 22,000 pounds (9980 kg). In addition, the weights of the following items are to be accommodated (approximate values):

Nacelle	4000 lbs. (1800 kg)
Bedplate	8300 lbs. (3740 kg)
Support Cone	2300 lbs. (1030 kg)
Yaw System	4000 lbs. (1800 kg)
(Includes bearing, brakes and disc)	
Mounting Frame	4000 lbs. (1800 kg)

The power generating equipment, except for the blades, is required to be housed by the nacelle and protected for the following conditions:

- Lightning

  The currents flowing in a lightning flash to ground are separated into three categories:

a) Return Stroke Surges	Peak current of up to 100,000 A or more. Duration of tens of microseconds.
b) Intermediate Currents	Peak current of up to 10,000 A or more. Duration of milliseconds.
c) Continuing Currents	Peak Current of up to 1000 A. Duration of hundreds of milliseconds.

- Environmental — The basic environmental requirements are discussed in Section 3.1, System Design Requirements; Environmental.

4.3.2 DESIGN APPROACH

The approach used in arriving at a final design of the nacelle equipment was to strive for a configuration that was pleasing to the eye of someone viewing the machine from the ground. This configuration also had to be consistant with the functional requirements of the nacelle equipment and, in addition, permit various maintenance operations needed during the life of the machine to be performed. The design developed for the MOD-0 machine met these criteria and was therefore used as a basis for the MOD-0A machine. Size increases were made in areas of the design where they would be beneficial.

4.3.3 SELECTED DESIGN

The design selected for the nacelle equipment is described on the following NASA drawings:

Assembly of Parts	CR758862 and CR758863
Bedplate	CR758877
Support Cone	CR758896
Mounting Frame	CF760271
Nacelle Members -	
Forward Center Shroud	CR758878
Rear Center Shroud	CR758879
Nose Cone	CR758880
Prop Cone	CR758881

The bedplate is a large steel weldment that serves as a mounting structure for the power generating equipment. It is 17.3 feet (5.28 m) long, 6.67 feet (2.03 m) wide and 2.29 feet (0.70 m) deep. These are approximate dimensions since the bedplate was designed to support many pieces of purchased hardware, located in various places as required to produce a functional arrangement for

the overall system. Figure 4.3-1 shows the bedplate and how it supports various pieces of equipment.

The bedplate is constructed of a common low carbon steel, SAE 1010-1030. The use of this material permitted welding to be used extensively in fabricating the plate.

Each structural weld in the main box section was radiographed to ensure that a sound structure resulted after welding. The bedplate for the MOD-0A machine is basically the same as that proven to be successful on the MOD-0 machine. The main box section was strengthened, however, to give higher load carrying capability. The criteria used for sizing the bedplate members was to assume that the machine was being operated with one blade missing. Under this condition, the bedplate was designed to keep stress levels below the yield strength of the material. Paint is used for corrosion protection on all surfaces of the bedplate.

The support cone is a structural member having a diameter of 71 inches (180.3 cm) at the base and 46.4 inches (117.8 cm) at the top. The cone is 36.9 inches (93.7 cm) high and is fabricated by welding, using a conical section 0.5 inches (1.27 cm) thick. All sections of the cone are made from SAE 1020 steel. After welding, the cone is thermally stress relieved prior to final machining. The top and bottom surfaces of the cone are machined to interface properly with the main yaw bearing and the mounting frame, respectively. The cone has two openings or windows in its sidewall to permit passage of drive shafts for the yaw drive system. Three heavy structural brackets are welded to the outside of the cone near the top. The purpose of these brackets is to provide mounting surfaces for the three yaw brakes that are used to prevent unwanted yaw motions of the nacelle.

The mounting frame is a structural assembly that mates with the bottom of the circular support cone and the top of the square tower. It provides support for all of the equipment mounted atop the tower. Figure 4.3-1 shows the mounting frame supporting this equipment on the service stand.

In plan view, the frame is basically a square, seven feet (2.1 m) on each side. The frame is 14 inches (35.6 cm) high except for the additional parts that hang from the underside of the frame a distance of 28 inches (71.1 cm). The purpose of this underhung structure is to provide a surface for mounting the drive motors for the dual yaw drive system. The mounting frame is fabricated by using ASTM A36 structural steel members. Bolts and welding are used for fastening members together, thus forming an assembly. After fabrication, the frame is painted with zinc chromate primer and finished with two coats of oil alkyd paint.

The nacelle is a sausage shaped shell structure as shown in Figure 4.3-2. It is eight feet (2.5 m) in diameter and 32 feet (9.8 m) in overall length. The purpose of the nacelle is to provide a streamlined housing for the power generation and other equipment located atop the tower. The housing protects the equipment inside from the corrosive effects of the environment and is very beneficial for providing the capability of year-round maintenance on the machine.

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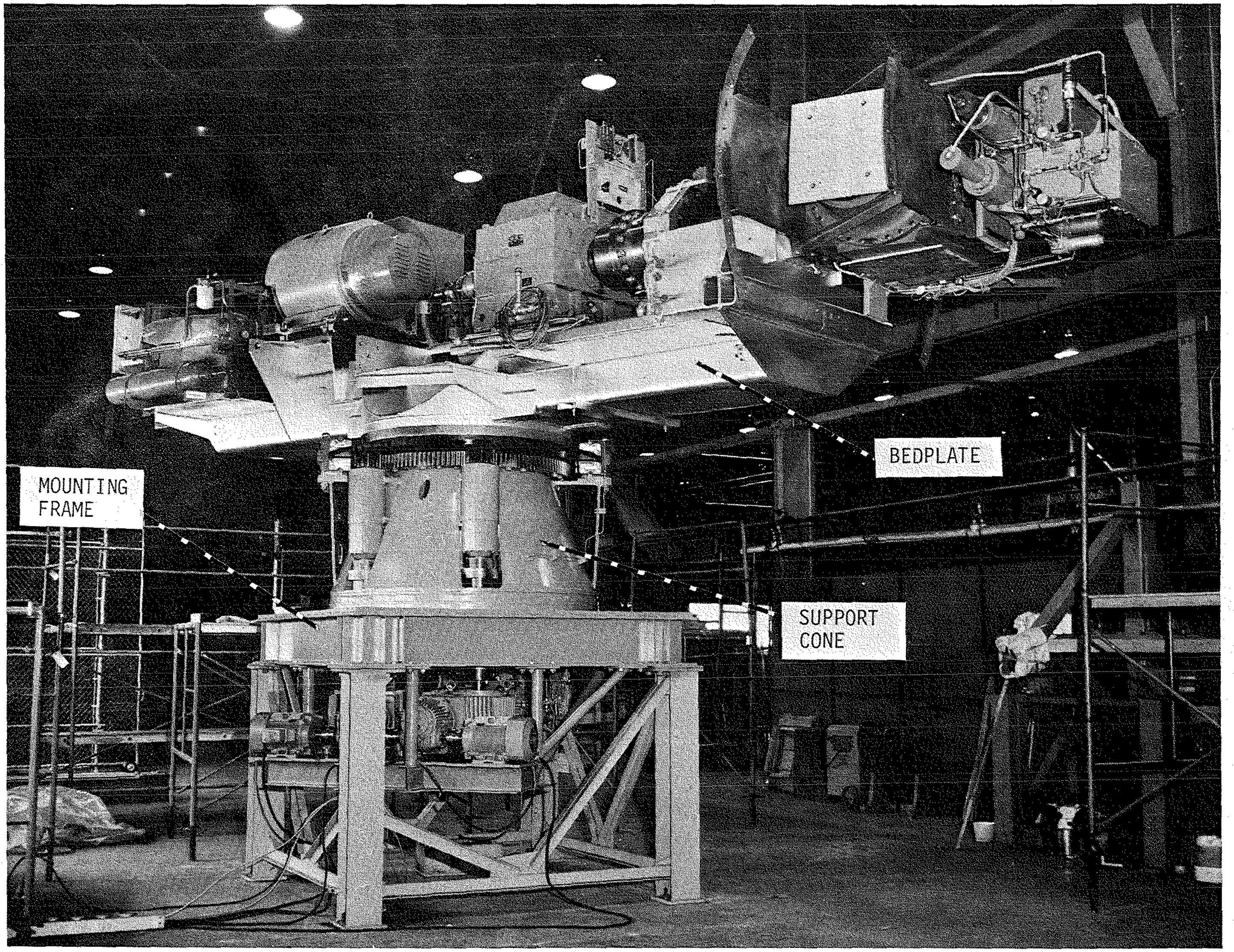


Figure 4.3-1. Bedplate, Support Cone, Mounting Frame, Service Stand, and Yaw System

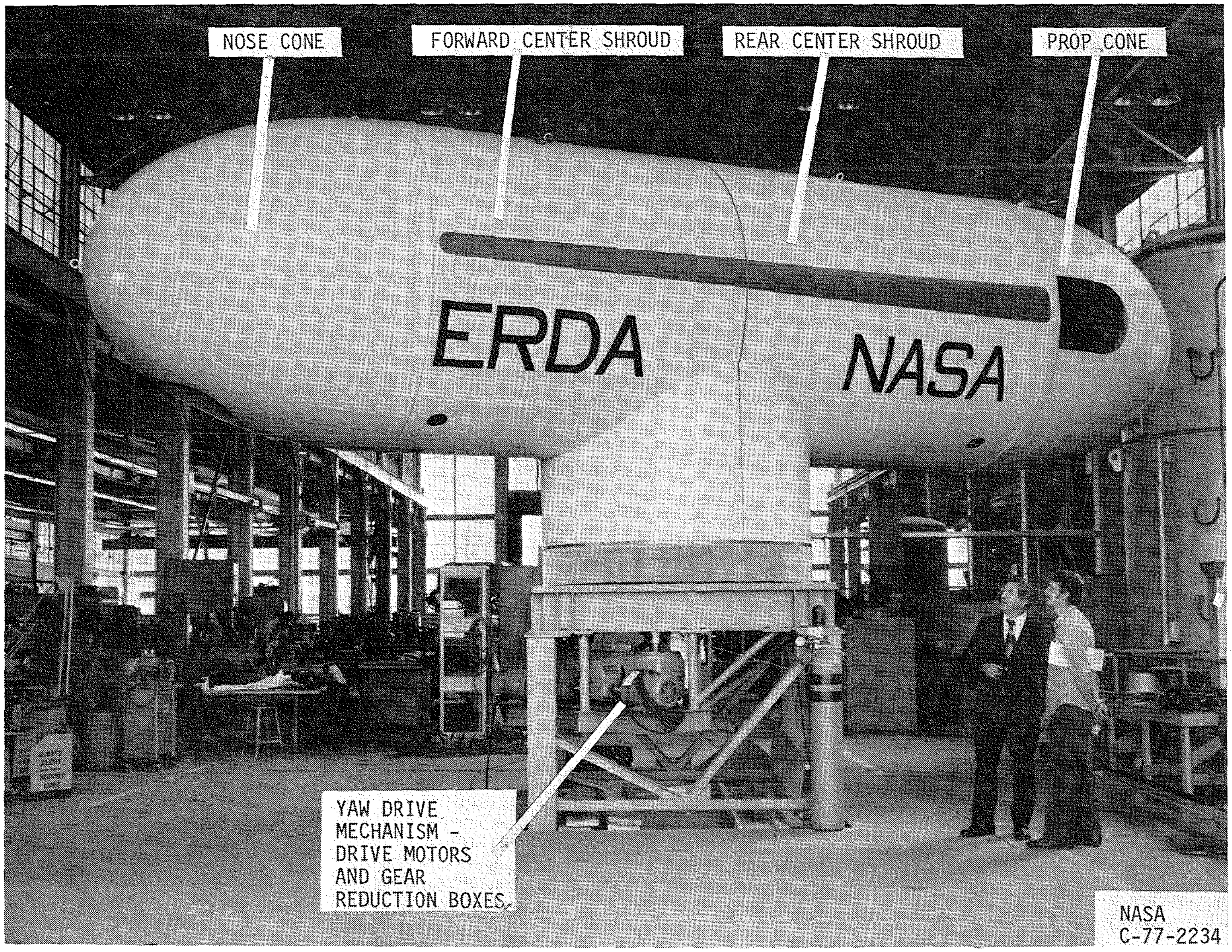


Figure 4.3-2. Nacelle

The nacelle is composed of four fiberglass sections, each having a wall thickness of 0.312 inches (0.792 cm) minimum. Three of the four sections are stationary while one, the prop cone, rotates with the blades during operation of the machine. A weather shield is provided between the stationary and rotating sections in order to prevent birds, water, snow, sand, etc. from entering or accumulating on the equipment inside the nacelle. The sections of the nacelle have internal flanges that permit attachment to each other and to the bedplate that is used for supporting the stationary sections. The flanges are designed to flex somewhat in order to accommodate thermal expansion differences between the fiberglass members and the steel bedplate. The rotating section of the nacelle is bolted to the hub of the low speed shaft and rotates with that shaft. The nacelle is made with a skirt that extends down 6.5 feet (1.98 m) below the axial centerline of the machine. This skirt protects the yaw bearing, bull gear, and brakes from rain and snow.

Hatches that are removable from inside the nacelle are included to permit cables needed for lifting the machine to be attached to eyes in the bedplate. These hatches are translucent and also serve as skylights for natural lighting. A screened opening is provided in the nose cone for the entrance of air needed to cool the oil in the hydraulic pitch control system.

4.4 YAW DRIVE

The entire MOD-OA machine mounted atop the tower is supported on a large turntable bearing which permits the machine to be turned when the wind direction changes. The turning action is achieved by a yaw drive mechanism that is described below. When turning is not required, that is, when wind direction is not changing, the machine is held from turning by three yaw brakes, also described below. The yaw drive control system must, therefore, synchronize the operation of the yaw drive mechanism with the yaw brakes.

4.4.1 YAW DRIVE MECHANISM

4.4.1.1 REQUIREMENTS

The yaw drive mechanism is required to perform two principal functions:

- Rotate the entire nacelle assembly about a vertical axis in order to achieve alignment with the prevailing wind direction.

- Provide torsional stiffness to reduce unwanted yawing oscillations.

The yaw torque induced in the bedplate-bull gear assembly is produced by wind loads on the blades as they rotate. This torque is mostly cyclic in nature with the following characteristics at rated conditions:

Steady Torque	13,000 ft. lbs. (17,620 Nm) (CW looking down)
Alternating Torque	43,000 ft. lbs. (58,300 Nm) (CW or CCW)
Frequency: (2 per rev.)	1.33 Hz

4.4.1.2 DESIGN APPROACH

The yaw drive mechanism design was developed from the MOD-0 design by using operational data obtained from that machine. This prototype machine at NASA LeRC's Plum Brook Station, near Sandusky, Ohio, was instrumented during operation and showed bending moments on the blades that were significantly higher than those predicted.

Examination of the harmonic content of the blade loads led to the conclusion that these loads were caused by nacelle yawing motion. As originally constructed, the nacelle was connected torsionally to the tower by means of a single yaw drive shaft. It was determined that the spring constant of this shaft in torsion produced a yawing resonance which resulted in large lateral motions of the rotor hub. These motions in turn were assumed to cause edgewise blade loads in a manner analogous to that known for airplane propellers.

To reduce edgewise loads, it was decided that, for the MOD-0A design, the single yaw drive be replaced by a dual yaw drive system. Nacelle motions would then be reduced, because of three factors: (1) avoidance of a resonance, which was of greatest significance, (2) stiffening the nacelle-to-tower connection, and (3) eliminating the free play present in the single yaw drive system.

4.4.1.3 SELECTED DESIGN

The design selected for the yaw drive mechanism is shown on the following NASA LeRC drawings:

Assembly	CR758862 and CR758863
Bearing & Gear Assembly	CD758933
Bearing Housing	CF758897
Yaw Drive Shaft	CF758898
Bearing Retainer & Seal	CF758899
Intermediate Yaw Drive Shaft	CD758900
Speed Reducer	CD758938

Figure 4.3-1 shows the yaw drive mechanism installed on the MOD-0A machine. The drive motors and gear reduction boxes are located on a structure that is underhung from the mounting frame. Two drive shafts extend vertically upward from the gear boxes, through cut-outs in the side wall of the support cone, and provide torque for the pinion gears that engage the bull gear teeth that are machined in the outer race of the main yaw bearing.

The yaw drive mechanism uses two worm drive gear boxes, each driven by a ten horsepower (7.46 kW) motor. The gear boxes and pinion drives are pretorqued against each other to 50,000 in-lbs. (5,649 Nm) at assembly. This is done to eliminate backlash in the gear drive members and to increase the torsional stiffness of the yaw drive system. The preload is obtained by turning the input shaft of one worm drive unit against the stationary unit, while sensing torque in the output shaft of the first unit. The preload is maintained by coupling the two input shafts of the worm drives while the assembly torque is being applied. This assembly procedure causes the units to rotate in synchronism.

The worm drive gear boxes are commercially available units identified as cone drives Model UV 73350C of the Excello Corporation. The unit characteristics are:

Input Speed	1750 rpm
Secondary Worm Speed	35 rpm
Rated Output Torque (Min.)	65,000 in-lbs. (7,344 Nm)
Output Torque (Max.)	105,000 ft-lb (11,860 Nm)
Unit #1-Primary Worm	RH helix
Secondary Worm	RH helix
Unit #2-Primary Worm	LH helix
Secondary Worm	RH helix

Operation of the yaw drive mechanism is coordinated with operation of the yaw brakes. When the control system initiates yawing, the pressure in the three yaw brakes is reduced to 100 psig (0.69 MPa) to permit the yaw drive system to turn the machine while the brakes are dragging on the disc. Higher pressures would create too much load on the yaw drive system while lower pressures would not give enough torsional (yaw) stiffness. With the brakes partially released, the two drive motors are turned on, and yaw motion begins. With the drive motors turning at 1745 rpm, the secondary worm of the gear reducer turns at 35 rpm and the bull gear, bedplate, et. al. turn at 0.1725 rpm.

Due to the cyclic nature of the rotor induced yaw moments applied to the bedplate, damping action is desirable during yawing. This damping is provided by the dragging of the yaw brakes as described above. The dragging effect is related to the hydraulic pressure applied to the brakes as shown in Figure 4.4-1. Testing to get this information involved driving the bull gear with the dual yaw drive mechanism while various pressures were applied to the brakes. The torque output of the drive system was monitored at 45° intervals and plotted versus brake pressure.

The dual yaw drive system can be set during assembly at various preload torques to give various stiffness valves. Figure 4.4-2 shows the relation between yaw torque and yaw rotation for several preload torque settings.

4.4.1.4 ANALYTICAL RESULTS

An analysis of the dual yaw drive mechanism involving the following components was performed:

- Worm Gearboxes
- Pinion Teeth
- Bull Gear Teeth
- Keys
- Shear Key
- Pinion Drive Shaft

The following loads were considered for each of the components:

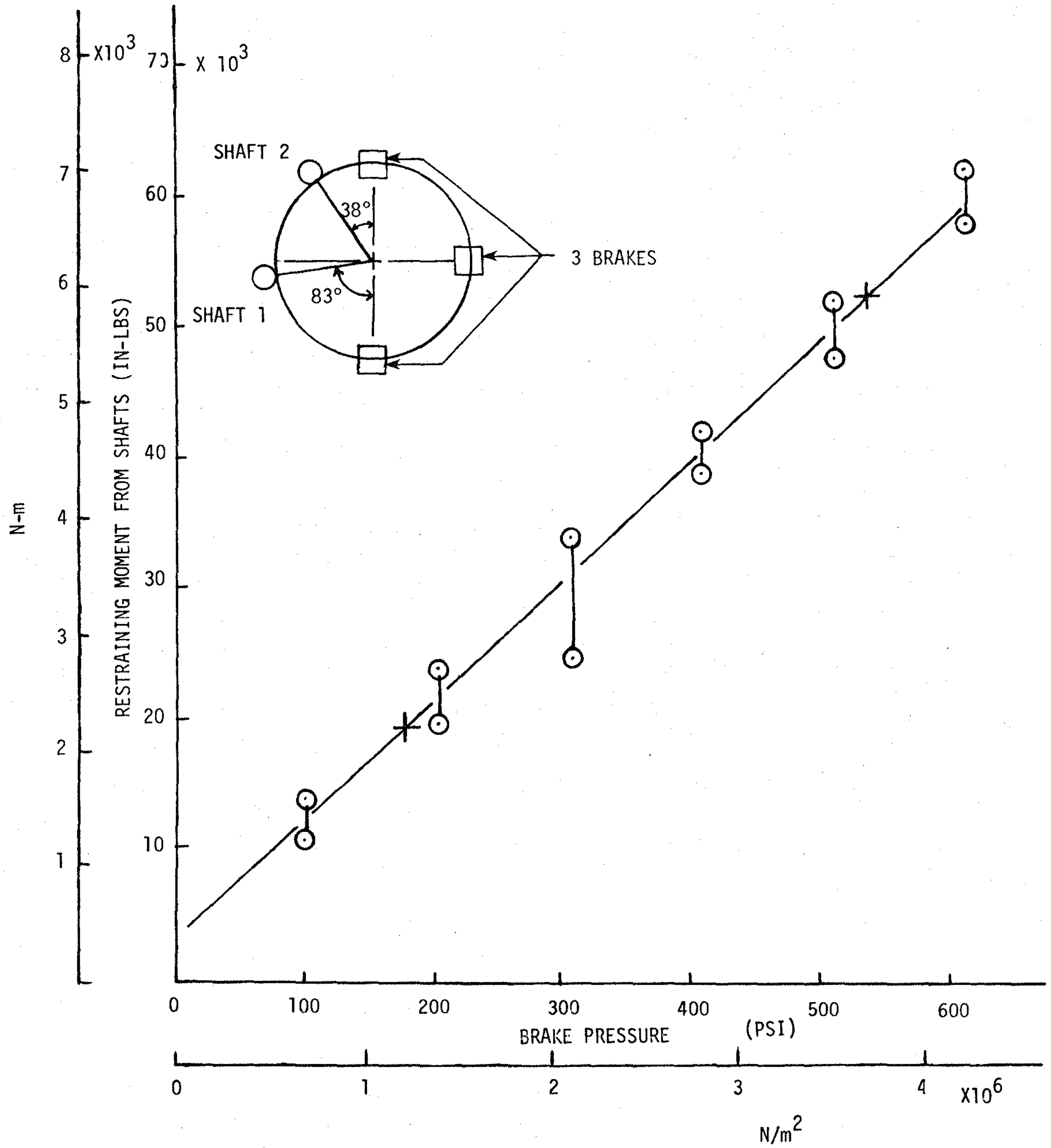
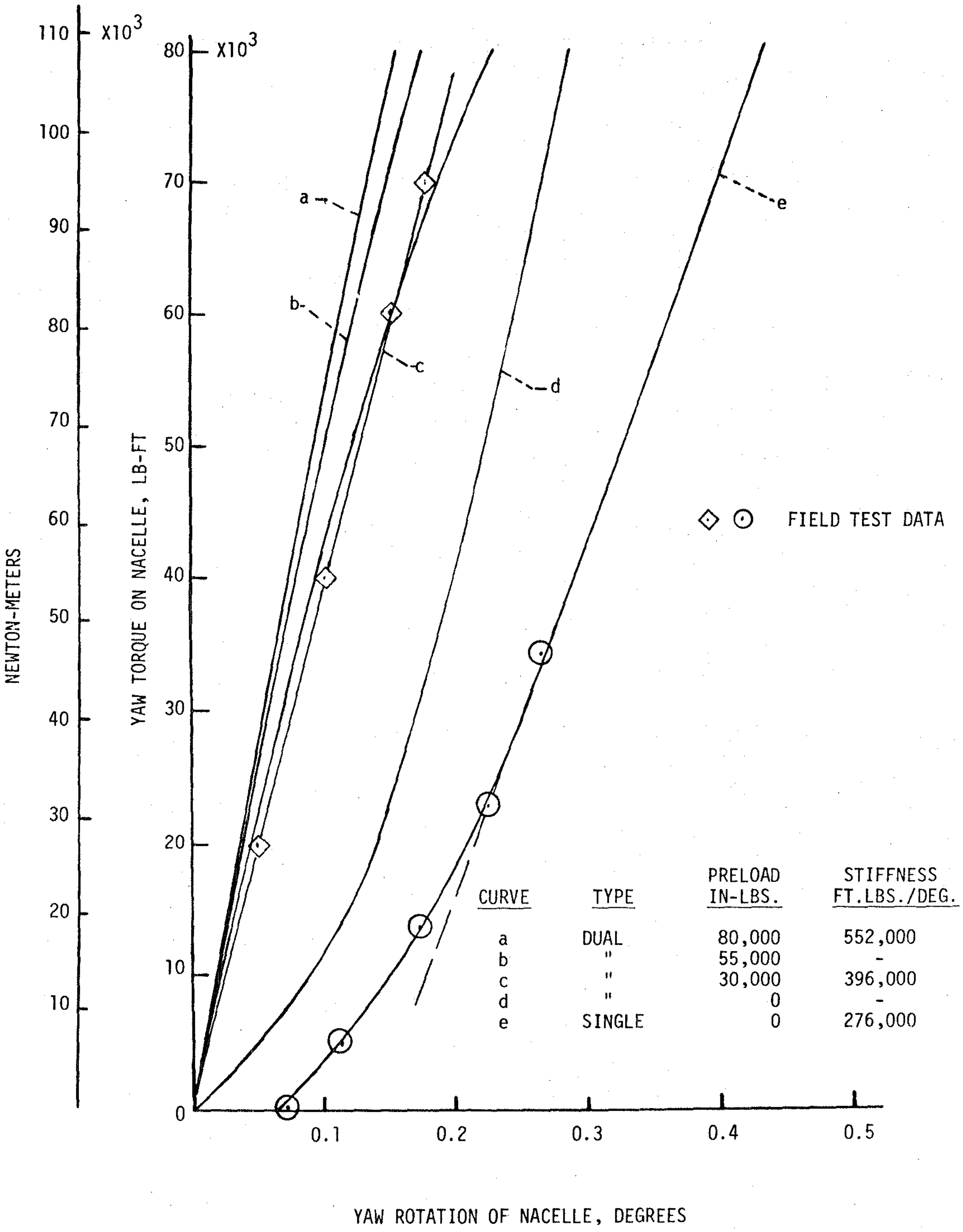


Figure 4.4-1. Effect of Brake Pressure on Restraining Yaw Moment



CURVE	TYPE	PRELOAD IN-LBS.	STIFFNESS FT.LBS./DEG.
a	DUAL	80,000	552,000
b	"	55,000	-
c	"	30,000	396,000
d	"	0	-
e	SINGLE	0	276,000

Figure 4.4-2. Yaw Torque Vs. Rotation for Several Preload Torques

- Limit Load - pinion shaft torque as limited by the shear key. This is a non-repetitive load that is to be compared to yield strength, brinelling, etc.

- Preload - Pinion shaft preload torque that is set at the time of installation. This is the prevailing load in the shafts during yaw movement with zero torque applied to the turntuable by the nacelle and is seen by the individual gear teeth as a cyclic load.

- Cyclic Load - This is a repetitive load applied to the turntable by the nacelle as a result of turbine operation and is superimposed on the preload. Values for this load are those stated above as requirements for the Yaw Drive Mechanism.

The load schedule and life were defined as:

- Limit Load - applied rarely during the life of the machine, one load pulse per occurrence (non cyclic/repetitive).

- Preload - applied continuously during the life of the machine.

- Cyclic Load - 80 cycles per minute for 3000 hours of each year (superimposed on the preload).

- Worm Unit Operation - three minutes of each hour for the entire life of the machine independently of the cyclic load of C above.

- Service Life of Machine - 20 years.

The primary conclusions of this analysis are as follows:

All the components are shown to be adequate for all the loads, but certain precautions must be taken with regard to fatigue. For all the components except the steel keys, it is necessary to limit the number of cycles of fatigue loading by applying the yaw brake when the drive is stationary.

That the major components all are similarly limited in fatigue and show comparable margins on the other loads demonstrates the balance of the design.

The shear key is somewhat marginal in fatigue even with the limited number of cycles. This is a necessary corollary of its being designed as the weak link in the chain. Because of this, these keys should be inspected after two to three years of machine operation. If at that time there have been no incidents of abnormal load to fail the key and the operating experience indicates that the likelihood of any seems small, it may then be decided to replace these with strong keys and forego the overtorque protection. The operating experience at that time will also show how the actual loads compare with those used in this analysis. If the actual loads are higher and/or the continued protection is needed, a replacement schedule should then be established for the shear keys.

Failure of a shear key, whether by abnormal load or by fatigue, would result in loss of preload. But since one of the worm units sees lower loads than the other (this was considered in the analysis), simultaneous failure of both keys either by abnormal load or by fatigue is very unlikely. The remaining key and one side of the system is capable of yawing the machine.

An individual assessment of each component mentioned above follows:

Worm Gear Box - The worm units are adequate for the cyclic load. Since the preload is holding out all backlash, the cyclic load is applied without shock. Operation under the steady preload is much less severe than with the cyclic load, and is shown to be within rating. The limit load is set by the worm units' limitation. Therefore, it is concluded that the cone drive UV 77350-C is adequate for all the loads if the yaw brake is applied when the drive is stationary.

Pinion Teeth - The pinion teeth are adequate for the limit load and the preload. The pinion teeth are also adequate for the cyclic load, except that if the cyclic load is applied for an extended time, the tooth contact surface can be expected to have some pitting or spalling. Therefore, the yaw brake should be applied whenever the yaw drive is not in motion, thus limiting the number of load cycles to about five percent of what it would otherwise be.

Bull Gear Teeth - The gear teeth are adequate for the limit load in bending, but the contact stress would cause brinelling. For this rare, non-repetitive overload, minor brinelling is not objectionable in this type of low speed gearing.

The gear tooth is adequate for the preload in terms of both bending stress and contact stress.

The gear tooth is adequate for the cyclic load in terms of bending stress and contact stress, but only if the reduced number of cycles is used. The reduction in cycles is achieved by applying the yaw brake when the yaw drive is not in motion.

Keys - All three keys are satisfactory for all three loading conditions.

Shear Key - Although the key is somewhat marginal in fatigue, the key shear stress at the peak cyclic load is 86 percent of yield so there should be no loss of preload from key deformation under the cyclic loading.

Pinion Drive Shaft - The pinion shaft is safe for all the loads. The most critical stress situation is the fully reversed bending fatigue in the snap ring groove. The analysis is conservative because:

- The torsional component of the stress does not actually reverse.
- The stress is the peak cyclic stress which, statistically, cannot always coincide with the shaft rotation.

4.4.2 YAW BRAKE

The "yaw brake" is actually three hydraulic brakes working together to prevent unwanted yaw motions of the nacelle. These brakes are mounted outside the support cone, on brackets near the top of the cone.

4.4.2.1 REQUIREMENTS

- The yaw brake must prevent the nacelle from turning when external moments as large as 66,000 ft-lbs (7,457 Nm) are applied to the nacelle.
- The brake actuation system must be independent of external supplies except for electricity.
- The brake system shall have two pressure levels. The high level will be applied when the yaw drive motors are off. The low level shall be applied when the yaw motors are energized. The high level shall be 1500-2500 psi (10.3-17.2 MPa) unregulated; the low shall be adjustable from 100 to 1500 psi (0.69 to 10.3 MPa) with an initial setting of 100 psi (0.69 MPa).
- The yaw actuation system shall be electrically interlocked so that the drive motors cannot be energized until the yaw brake pressure has reduced to the low level.
- Yaw brake pressure shall be displayed on the control room control panel.
- Alarms to the fluid systems safety circuit shall trip when brake pressure drops below the low level, and normal supply system level.

4.4.2.2 DESIGN APPROACH

The yaw braking design utilized on the MOD-0 machine was satisfactory for the MOD-0A machines and therefore would be used.

4.4.2.3 SELECTED DESIGN

The design selected for yaw braking involves the use of three brake assemblies that are commercially used on heavy duty earth moving equipment. The three hydraulically actuated assemblies (Goodyear Mel SCL-19-2) are mounted 90° apart on brackets welded to the outside of the support cone. The nacelle/bedplate assembly is made with a thick brake disk that is positioned horizontally and bolted to the bull gear which rotates with the nacelle. Braking action is produced when hydraulic fluid is forced into the brake assemblies thereby activating the brakes and causing them to grip the brake disk and prevent yaw motion of the nacelle.

Figure 4.4-3 shows one of the three yaw brakes installed on its mounting bracket. Each assembly contains six pistons for providing gripping action under hydraulic pressures up to (2500 psig (17.2 MPa). The brake disk is 1.25

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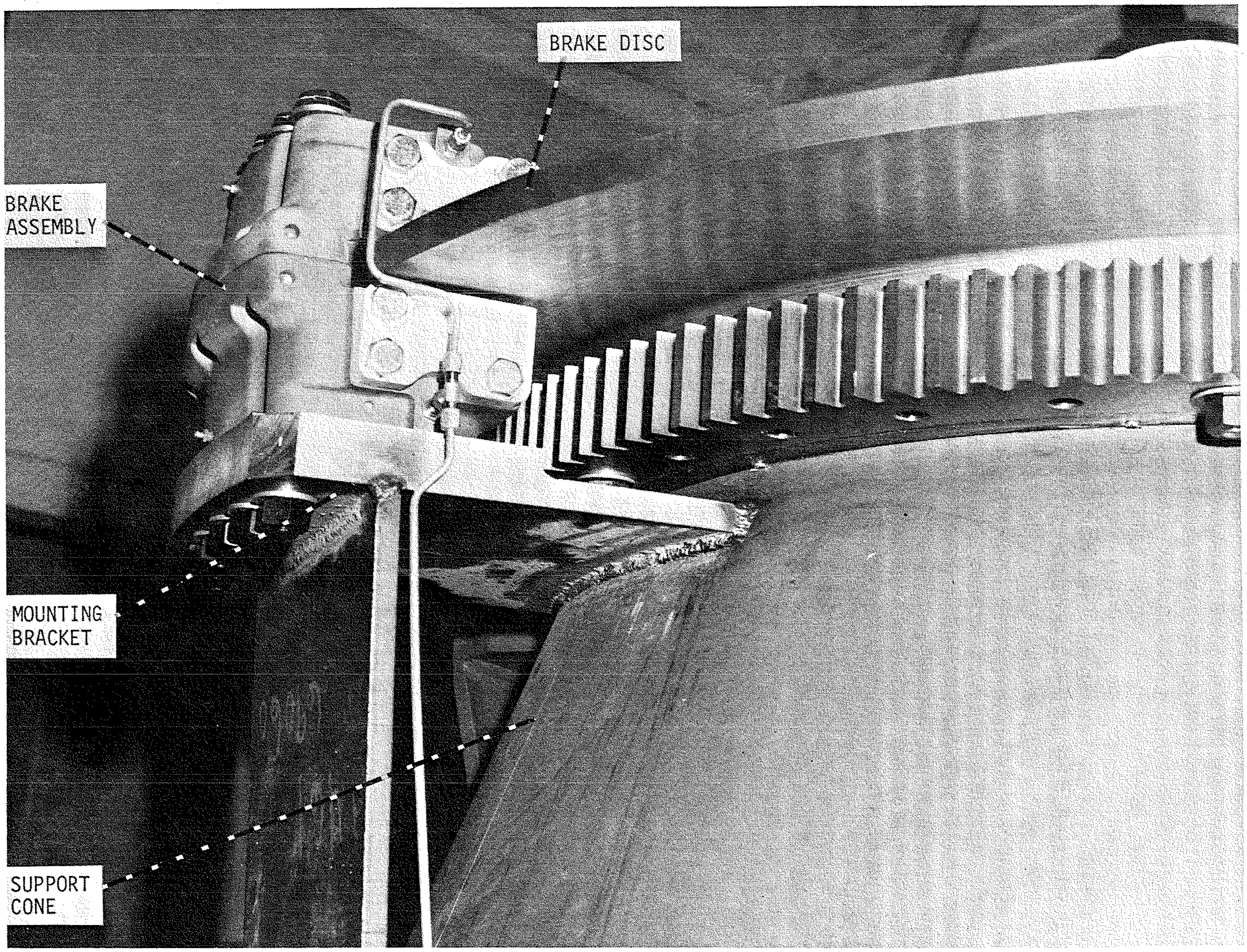

Figure 4.4-3. Turntable Bearing and Gear Assembly

inches (3.2 cm) thick and 72 inches (1.83 m) in diameter. The brake linings are not physically attached to the six pistons but are retained within the caliper body by removable bolted-on end plates. Standard organic linings having a contact area of 102 square inches ($6.58 \times 10^{-2} m^2$) per brake are used. The brake bleeding system is designed assuming that the brake is mounted on a vertical disk. Since the yaw brake disk is horizontal, care must be taken to get proper bleeding. Each assembly weighs approximately 214 pounds (97.1 kg).

The hydraulic system for activating the yaw brakes is described on NASA Dwg. No. CF759019 and CF760485 (W1015F80).

4.5 TOWER AND FOUNDATION

The MOD-OA tower and foundation are designed to provide a rigid support for the nacelle. Figure 4.5-1 shows the nacelle assembly complete with the rotor and yaw drive system being prepared for assembly onto the completed tower/foundation installation. The tower configuration is a welded tubular space truss. The nacelle assembly mounting frame bolts to the top of each of the four tower corner legs, which, in turn, are bolted to the concrete foundation.

The tower/foundation supports the WTG machinery at a 100 foot (30.5 m) hub height providing ample ground clearance for the 125 foot (38.1 m) rotor. Total supported weight is approximately 45,000 lbs (20,400 kg). The tower weighs about 44,000 lbs (20,000 kg) and is installed on a 34 foot (10.4 m) square by 4 foot (1.2 m) deep reinforced concrete mat foundation.

4.5.1 TOWER

The MOD-OA WTG tower is a four-legged 93-foot (28.3 m)-high lattice structure tapering from 30 feet (9.1 m) square at its base to about seven feet (2.1 m) square at the top. The tower is similar to that of the MOD-0 100 kW turbine installed at the NASA Plum Brook Station near Sandusky, Ohio. The changes made in the MOD-OA tower were designed to improve the bending and torsional stiffness of the tower and to decrease the tower "shadow" or wind velocity perturbation downwind of the tower.[36]

The MOD-OA tower uses eight inch (20.3 cm) extra strong pipe for the vertical corner legs and tubular horizontal and diagonal members. The MOD-0 tower used standard thickness pipe legs in the upper portion of the tower. That unit also used channel and angle shaped horizontal and diagonal members installed using corner gussets. In addition, service stairs and elevator rails were originally installed in that tower. Note the wind blockage area of the MOD-0 tower in Figure 4.5.1-1 compared to the relatively clean, open MOD-OA tower in Figure 4.5-1.

4.5.1.1 REQUIREMENTS

The basic tower configuration requirement is to support the nacelle with its WTG machinery and rotor at the proper height above the ground. The tower must

interface with both the yaw cone (nacelle) and foundation. The interface connections must be structurally adequate, yet permit ease of assembly and disassembly. In addition the tower arrangement must permit personnel access to the nacelle and provide for routing of electrical power and instrumentation conductors. The tower envelope is limited to provide adequate rotor/tower clearance.

The tower has several performance requirements. These include the areas of mechanical vibration and aerodynamics. Structurally, the tower vibration modes must be decoupled from the rotor frequencies (one per revolution and two per revolution) to prevent resonances excited by the periodic rotor forces. Aerodynamically, the tower must be designed to minimize the reduction in wind speed in the wake of the tower since the downwind rotor blades must pass through the wake during each revolution. This local disturbance in the wind profile is one of the major sources of blade excitation.

The structural requirements of the tower apply to each and every member as well as the various joints. In addition the nacelle and foundation interface designs must be capable of withstanding the design and operating loads. The design load condition for the tower is the 150 mph or 67.0 m/s (at hub height) hurricane wind loading. The tower must withstand this load with margin against yielding or buckling of members or deterioration of connections.

The tower design loadings include both live and dead loads. The American Institute of Steel Construction design criteria is used to evaluate the structure. The tower is a permanent WTG structure designed for a 50 year life.

The environmental requirements of the tower are limited to protection against corrosion and lightning strikes.

Other practical tower requirements exist due to its unusually large size and the relatively remote installation. The tower must be shipped to the site by truck from the point of fabrication. Factory assembly of the tower must be limited to components and subsections that can be shipped. However, field fabrication must be minimized because of the difficulty in achieving dimensional control and quality control in field conditions.

4.5.1.2 APPROACH

The fundamental approach taken in the MOD-OA tower was to design a unit that rigidly supports the nacelle. This effectively produces a fixed axis rotor, the design approach selected for the MOD-OA rotor. To accomplish this approach, the tower deflections under load must be small. System response due to rotor/hub interaction forces, in particular, must be small.

Considerable experience was gained with the steel truss tower in the MOD-O WTG. Since the rigid tower concept was also selected for MOD-OA, that experience was utilized to the greatest extent possible. The MOD-OA machinery and rotor weights are somewhat greater than those for MOD-O. Therefore it was decided to stiffen the tower as much as practical to obtain approximately the same tower natural frequency level as in MOD-O.

Early MOD-OA test results showed that blade root stresses were about 60 percent higher than the expected design values. This finding led to numerous investigations into the possible sources of the discrepancy. One area where the investigation proved fruitful was in the examination of the rotor wind profile disturbance by the tower.[36, 43] It was found that the MOD-0 wake with the original tower con iguration shown in Figure 4.5.1-1 was more severe than expected and could be greatly improved by removing the stairs and elevator rails. These modifications were made and resulted in a significant reduction in blade stresses.

The approach taken to the MOD-OA tower aerodynamic design was based on the MOD-0 findings. First, the tower was designed to be as open and "clean" as possible. Then, changes in members and joining methods were considered that were impractical in the already existing MOD-0. Model tests were conducted in a wind tunnel to evaluate various potential members and joints. MOD-0 used channels and angles and end connections bolted to fairly large gusset plates. Welded tubular members without gusset plates were selected for MOD-OA because of the improvements in tower shadow.

4.5.1.3 SELECTED DESIGN

The tower is sized to a large degree by the MOD-OA WTG basic design specification. The 93 foot (28.3 m) height of the tower is determined by the desired rotor height of 100 feet less half the nacelle diameter less a suitable height for the yaw support cone and mechanism. The tower is about seven feet (2.1 m) square at the top providing reasonably broad supporting points for the yaw cone mounting frame. Also this provides sufficient space in the top area of the tower for the yaw drive system, for access to this system and for access to the nacelle through the yaw cone. The tower width increases only slightly down to the 40 foot (12.2 m) elevation maintaining ample rotor blade/tower clearance. Below this level the tower size gradually increases to about 30 feet (9.1 m) square at the bottom. This results in a broad, stable tower base with reasonable interface loads at the tower/foundation interface.

The external tower arrangement is shown in Figure 4.5-1. The tower uses eight inch (20.3 cm) extra strong vertical corner pipes. In the upper section of the tower, where the wake affects the rotor blades, four and five inch (10.2 and 12.7 cm) round pipes are used for the horizontal and diagonal structural members. In this section of the tower the numerous horizontal and diagonal members are carefully fitted and welded together, eliminating the necessity for gusset plates used in the MOD-0 joints.

The upper portion of the tower (above the break) was factory assembled and shipped to the site as an unit. The lower corner legs, horizontal members, and diagonals were assembled to the upper tower section at the site. Gussets, bolted joints, channels, and angles are used in this lower section of the tower since the rotor does not pass through the air flowing through this portion of the tower. The MOD-OA tower is shown in Figures 4.5.1-2 and 4.5.1-3 during a trial assembly at Meyer Industries. The upper and lower portions of the corner pipes are field welded together during final assembly just above the break. Figure 4.5.1-4 shows the detail of typical round piping welded joints. Figure 4.5.1-5 shows a typical bolted gusset joint.

Figure 4.5-1. Nacelle Assembly Installation on Tower

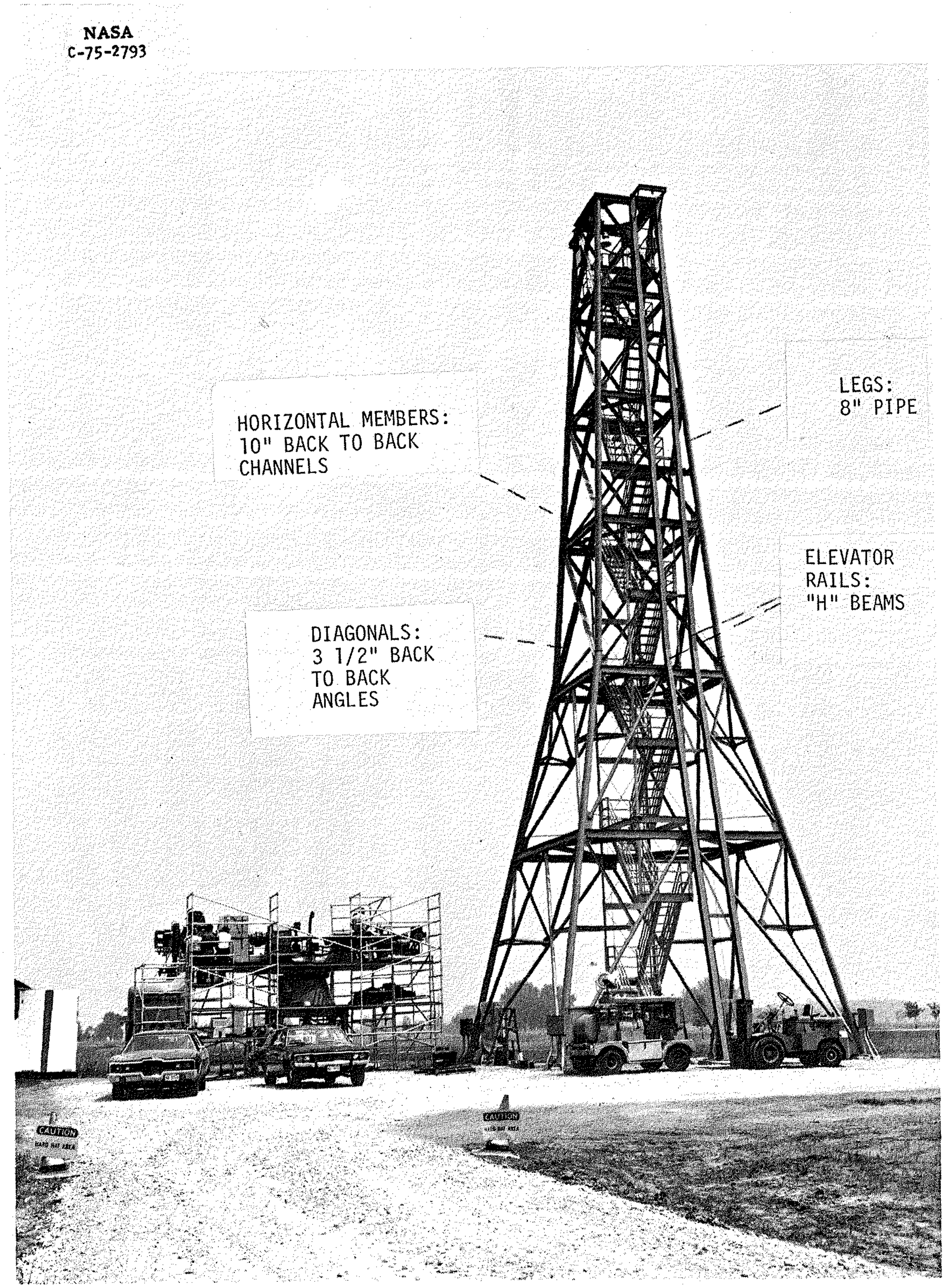

Figure 4.5.1-1. Original MOD-0 Tower with Service Stairs and Equipment Rails

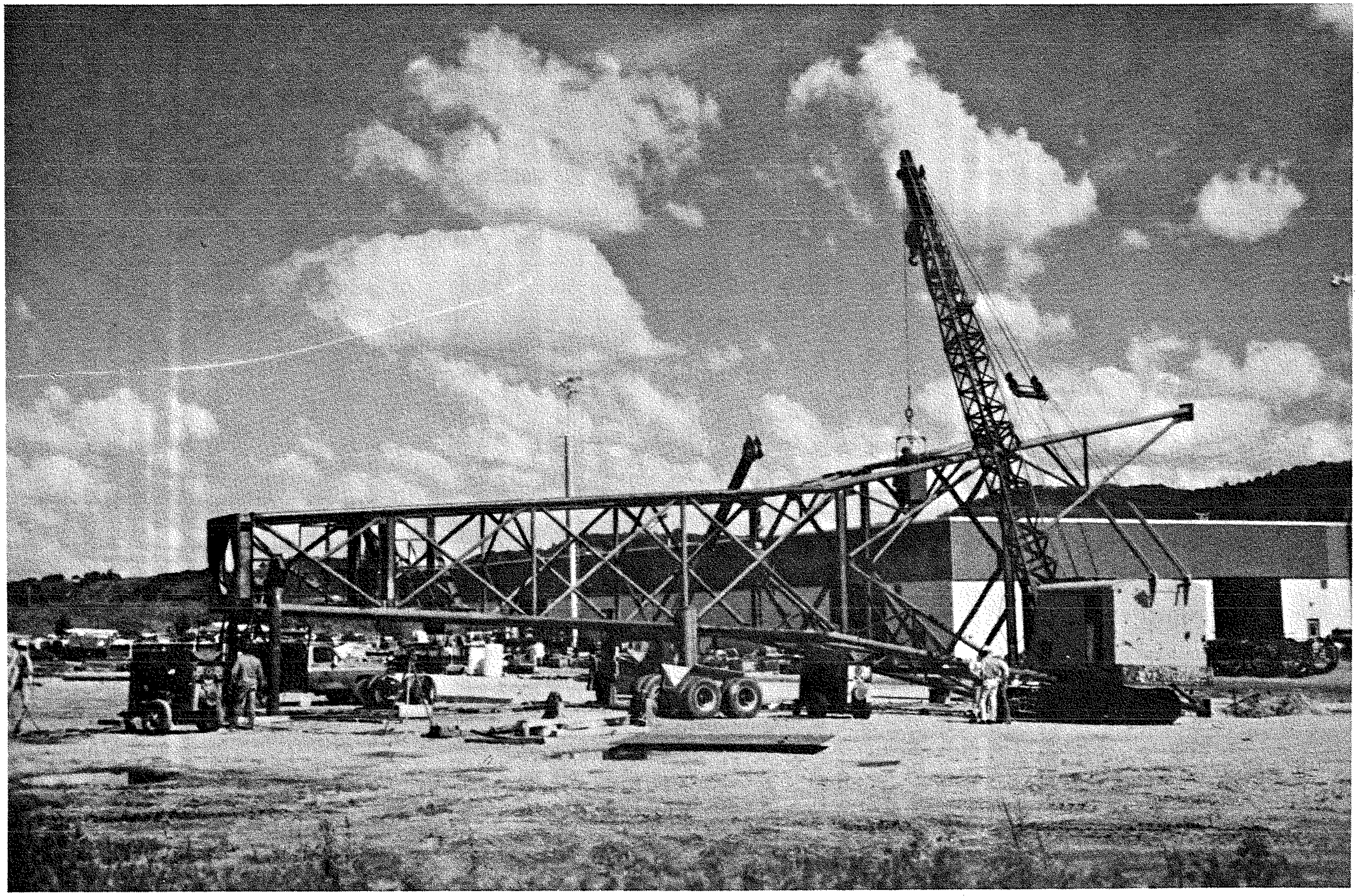

Figure 4.5.1-2. MOD-OA Tower During Trial Assembly at Manufacturer (Side View)

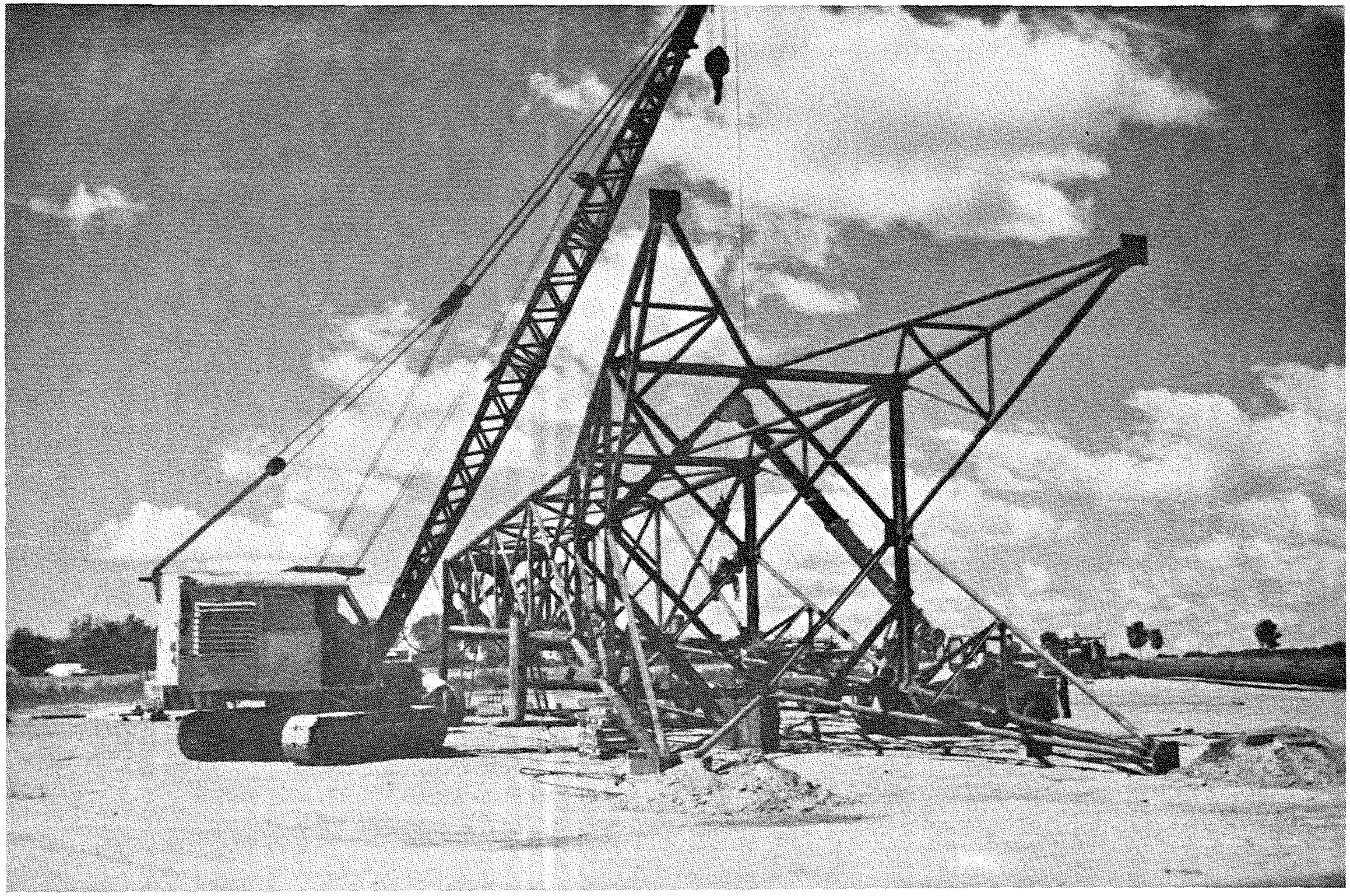

Figure 4.5.1-3. MOD-OA Tower During Trial Assembly at Manufacturer (Bottom View)

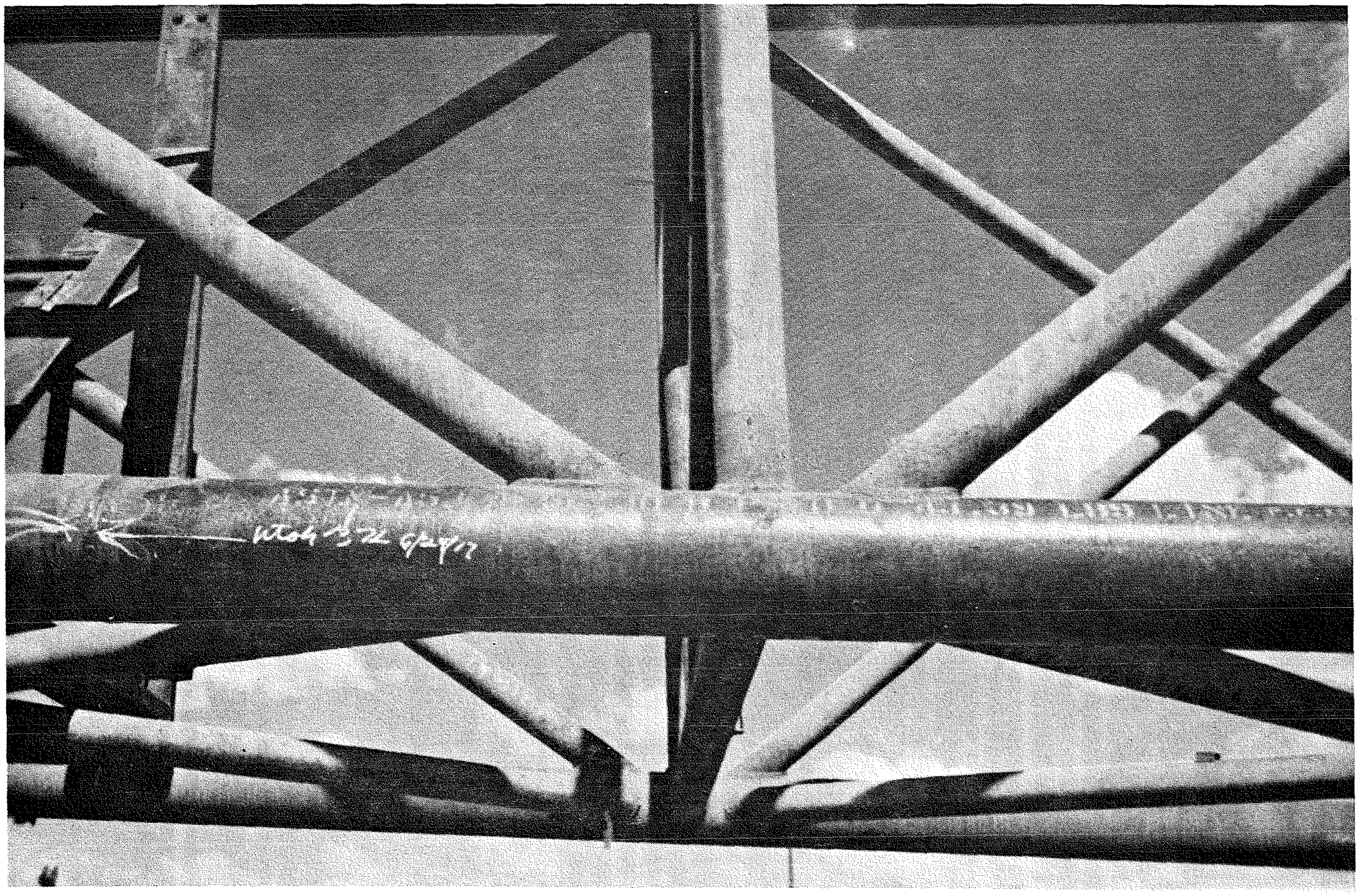

Figure 4.5.1-4. MOD-OA Tower Round Pipes and Welded Joints

Figure 4.5.1-5. MOD-0A Tower Gussets, Bolted Joints, Channels in Lower Section of Tower

The tower is defined completely in NASA Dwg. Nos. CF758948, CF758949 and CF758950 (W1015F70). The tower uses ASTM A53 pipe and A36 plate material. It is painted to provide corrosion protection.

The tower legs are bolted to the grounded mounts (see description of grounding system in Section 4.5.2.3) provided in the foundation, thereby grounding the entire WTG against lightning strikes. The four hollow eight-inch tower corner legs are used as conduits to protect the various cables. The power, instrumentation, and control cables were all installed in separate tower legs to minimize interference. This design for the cabling system also reduced, the tower shadow effects, by keeping the tower as open as possible. The completely assembled WTG as prepared for formal dedication ceremonies is shown in Figure 4.5.1-6.

4.5.1.4 SUPPORTING ANALYTICAL RESULTS

The original MOD-0 tower configuration with stairs and elevator rails, in addition to the tower itself, perturbed the free stream wind profile drastically at the downwind rotor. Wind tunnel tests showed that, in the wake of the tower, the local wind velocity slowed to as little as three percent of the free stream velocity and averaged as low as 55 percent of the free stream value at some wind directions.[43] Removal of the stairs and elevator rails increased the local velocities to at least 48 percent and the average to 72-85 percent of free stream velocity. Using round members throughout and removing gusset plates increased the minimum velocity to 60 percent and the average to 76 to 92 percent of the free stream value. Therefore the previously discussed design choices were made in the MOD-OA tower design.

The tower was designed structurally for the 150 mph (67.0 m/s) hurricane load at rotor height plus deadweight. The wind load is based on the front face area plus half of the back face area. The drag coefficients used are 2.0 for flat members and 0.67 for round members. No additional gust load was used. The 150 mph (67.0 m/s) wind velocity at rotor height corresponds to approximately 123 mph (55.0 m/s) nominal wind speed at the 30 foot (9.1 m) reference height. Figure 4.5.1-7 shows the resulting tower wind loading and dead load.

A NASTRAN computer model of the tower was developed for several purposes. Previously a MOD-0 model was developed with a stationary rotor.[45, 46] The model was used to calculate the system natural frequencies since it was desired to decouple the tower modes from the rotor frequency. A confirmation test on the MOD-0 system was run to verify the calculated modes. Test and analysis agreement was good. The MOD-OA tower model is essentially the MOD-0 model with new members and updated nacelle weight. The prime structural improvement in the MOD-OA tower is the increased thickness in the upper corner pipe members. The MOD-OA NASTRAN tower model fundamental frequency was calculated to be 2.2 Hz, significantly greater than the rotor 1p and 2p frequencies of 0.67 and 1.33 Hz.

The hurricane wind and dead weight loads were also applied to the model and the loads were calculated in each truss member. The allowable loads were

Figure 4.5.1-6. MOD-OA Fully Assembled

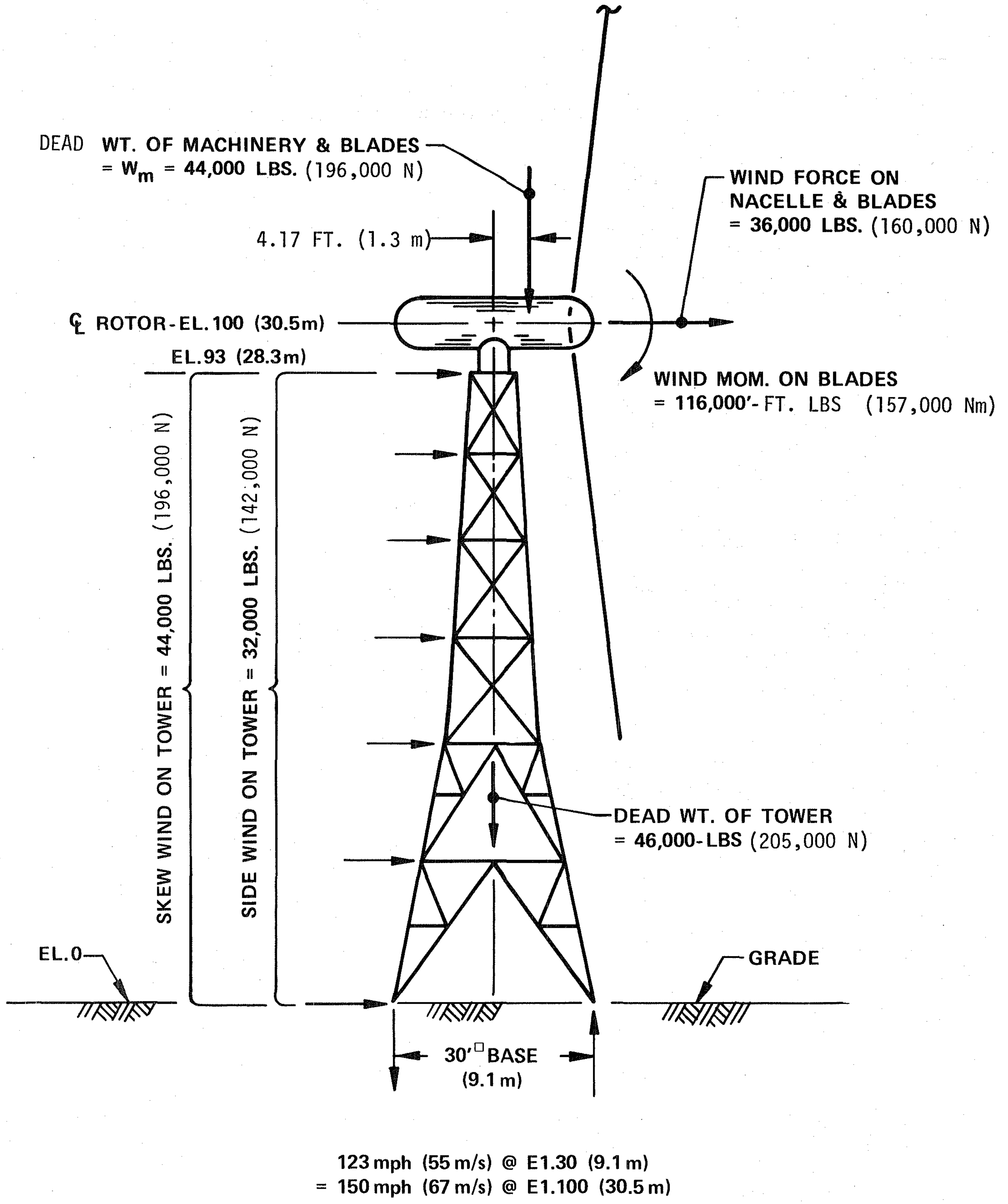

Figure 4.5.1-7. Tower Hurricane Load Plus Deadweight

calculated for each member considering the type of end connection as well as the various applicable failure modes. The possible failure modes for the hurricane load included tensile and compressive yielding, compressive buckling, end connection weld failure, and end bolt shear failure. All members are acceptable using AISC criteria. The NASTRAN model was also used for a fatigue analysis reported in Section 4.8.2. Additional calculations were made using classical stress analysis methods to evaluate local areas such as the nacelle mounting frame, the leg anchor plates and shear lugs, and the anchor bolts.

4.5.2 FOUNDATION

The tower is mounted on a reinforced concrete mat foundation as shown schematically in Figure 4.5.2-1. The foundation is sized solely on the magnitude of the wind and dead loads. The mat is 34 feet (10.4 m) square and the thickness is four feet (1.2 m). The concrete is heavily reinforced near its upper and lower surfaces to withstand the gross section bending moments. Integral features of the mat include the four tower mount pads, wiring conduits, and the control building base. The WTG foundation and the assembly stand foundation are completely defined in NASA Dwg. No. CF760300 (W1015F86).

4.5.2.1 REQUIREMENTS

The primary foundation configuration requirement is to provide an essentially rigid base compatible with the WTG tower and the control building arrangments. In addition, the foundation must provide suitable penetrations for the various electrical power, control, and instrumentation conductors. Also the base of the equipment and personnel hoist must be secured by the foundation.

The basic performance requirement of the foundation is to rigidly support the WTG/tower assembly under environmental and operating loads. The MOD-0 foundation supports that WTG on bedrock which is only 25 feet (7.6 m) below ground level. However, many other potential WTG sites differ from the Plumbrook site in that bedrock may be several hundred feet below ground level. Therefore an additional more specific support requirement was applied to the MOD-OA, Clayton foundation.

This additional requirement is that the foundation be capable of supporting the WTG tower without excavation to or penetration to bedrock (a design capable of universal application to nearly any site independent of depth to bedrock).

The structural requirements of the foundation include the local tower leg attachment requirements, the gross mat section strength requirements, and the foundation/soil stability requirements. The foundation must support the WTG under 150 mph or 67.0 m/s (at hub height) hurricane wind loading with margin against sliding or tipping.

The foundation sizing requirements include live and dead loads plus the soil bearing characteristics with the appropriate ACI (American Concrete Institute) rules for the mat, concrete, and reinforcing steel. The design life of the foundation is that of static components of the WTG, 50 years. The cost of the

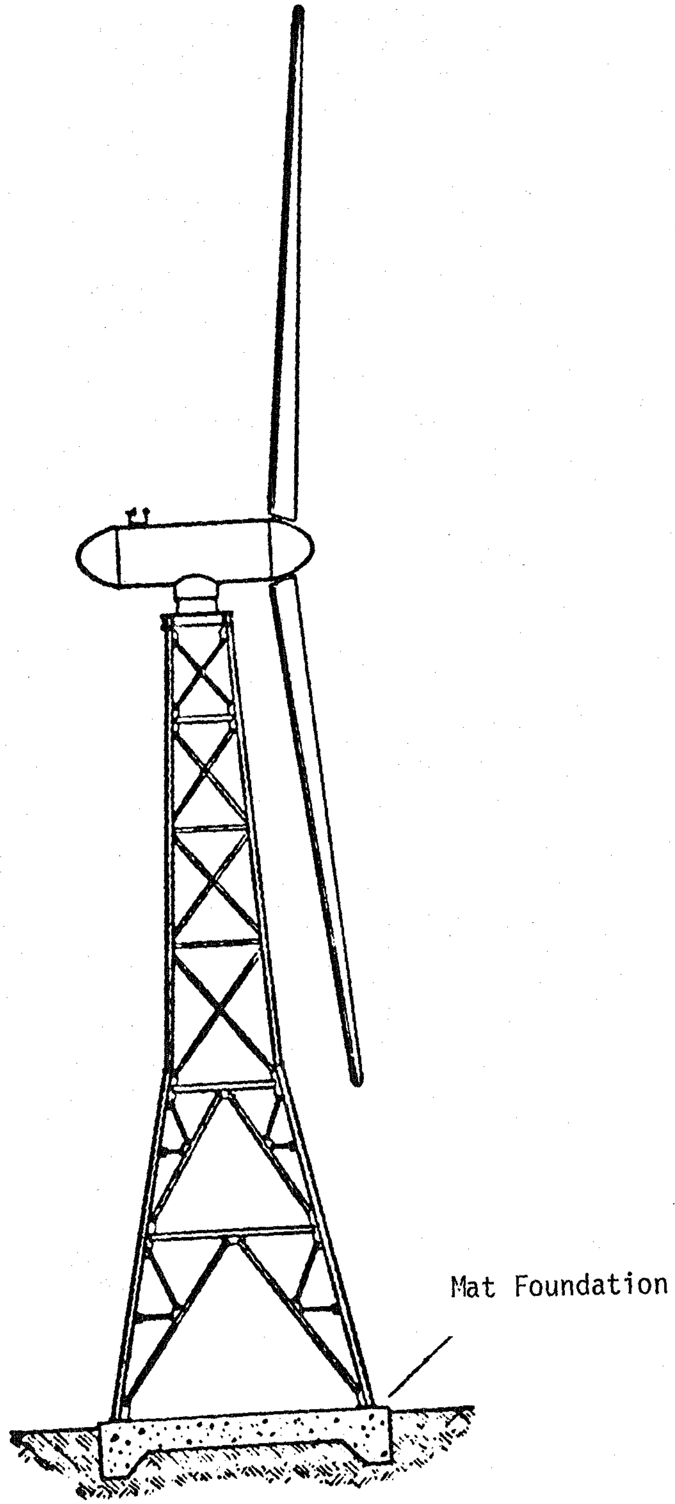

Figure 4.5.2-1. MOD-OA Wind Turbine

foundation is a consideration but the functional and structural adequacy and schedular requirements are overriding concerns. The more or less conventional foundation of the MOD-0A series of WTG's must be more than adequate to ensure successful testing of the highly experimental rotor and nacelle mounted equipment.

The environmental requirements of the foundation include protection against corrosion, erosion, water accumulation, frost and freezing. In addition, to minimize or prevent WTG damage during lightning strikes, a requirement exists to adequately ground the tower through the mount and mat rebar into the soil.

4.5.2.2 APPROACH

The foundation design problem was approached in a straightforward manner. It was decided that a mat type foundation would be developed for the MOD-0A Clayton WTG that could be used for nearly any site more or less independent of the nature of the soil or the depth to bedrock. This foundation could then be used for the entire family of MOD-0A machines with minimal site related redesign.

It was decided that the mat should be sized to prevent sliding over its soil bed with a coefficient of friction of 0.2 or tipping and bearing locally on the soil with pressures of more than 4000 lbs/ft^2 or 191,500 Pa (safe for any soil except loose fine sand or soft clay). Sufficient steel reinforcing bars are provided near the upper and lower mat surfaces to provide both positive and negative pad bending and shear strengths exceeding applied loads.

4.5.2.3 SELECTED DESIGN

The 34 foot (10.4 m) square by 4 foot (1.2 m) thick mat dimensions were selected based on the 30 foot (9.1 m) square tower base (leg spacing) plus the foundation design loads for a 150 mph or 67.0 m/s (at 100 foot or 30.5 m hub height) hurricane wind load plus nacelle and tower dead loads. Figure 4.5.2-2 shows workmen finishing the surface concrete for the mat and installing forms for the control building base. Figure 4.5.2-3 shows the mat complete and ready for installation of the tower and control building and final site grading.

Some additional structural detail of the mat is shown in the next two photographs. Figure 4.5.2-4 shows the reinforcement rod arrangement before pouring of the concrete. The rods are arrayed in two layers near the top and bottom surfaces of the mat. The rods are #8 (ASTM A615, GR60 with 60 ksi yield) spaced on 12 inch (30.5 cm) centers. Also shown in this figure are wiring conduits cast integrally into the mat. Figure 4.5.2-5 shows a typical tower leg mount point. Note the depression which mates with the tower leg shear keys. The four mount bolts are welded to a plate which is imbedded in the mat. The plate is grounded to the mat rebar.

Not shown in these figures is the mat grounding system. Two complete loops of bare copper ground wire surround the foundation. The total wire length is

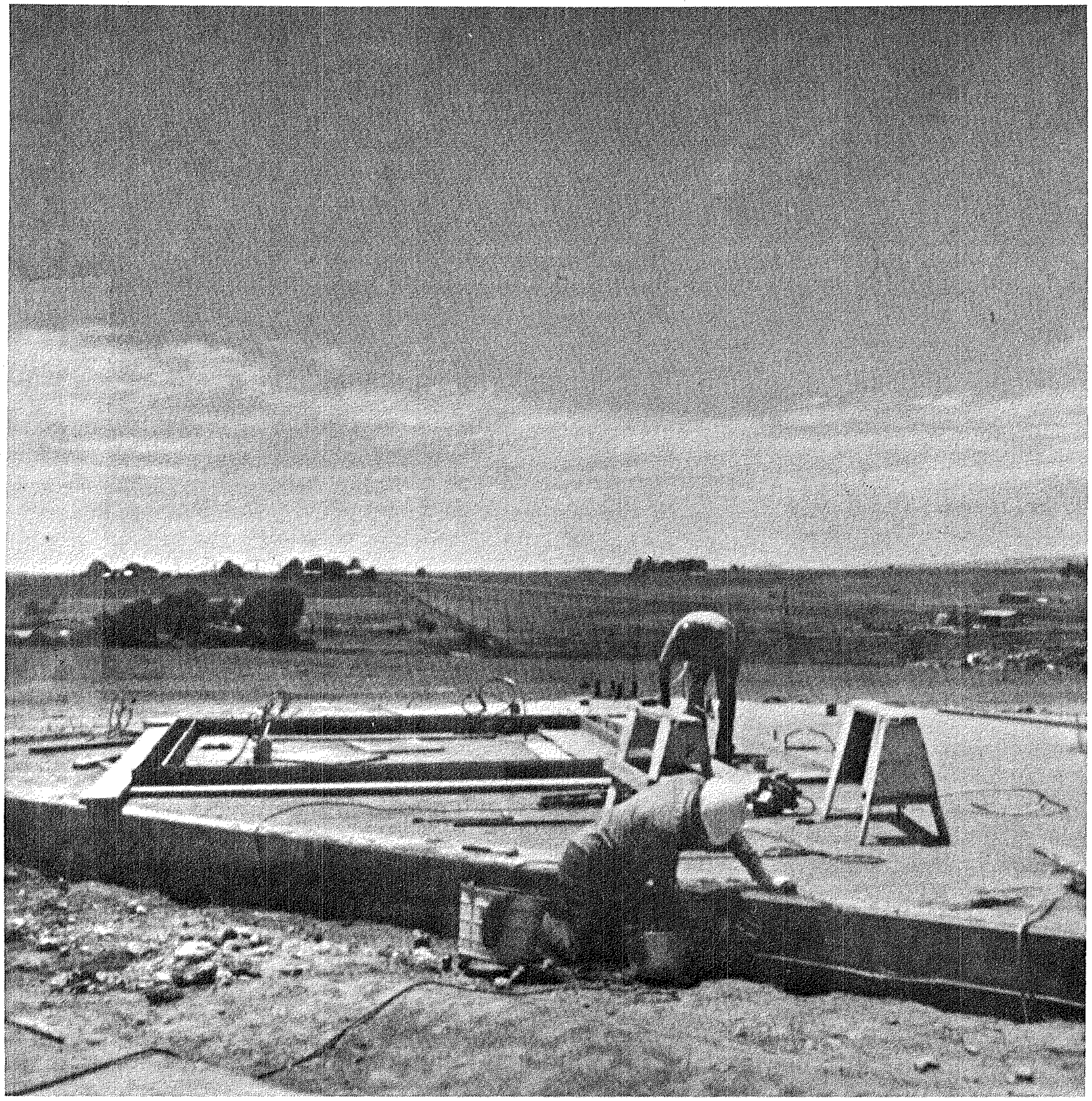

Figure 4.5.2-2. MOD-OA Mat Foundation
(Forms still in place)

Figure 4.5.2-3. Completed Mat with Control Building Base

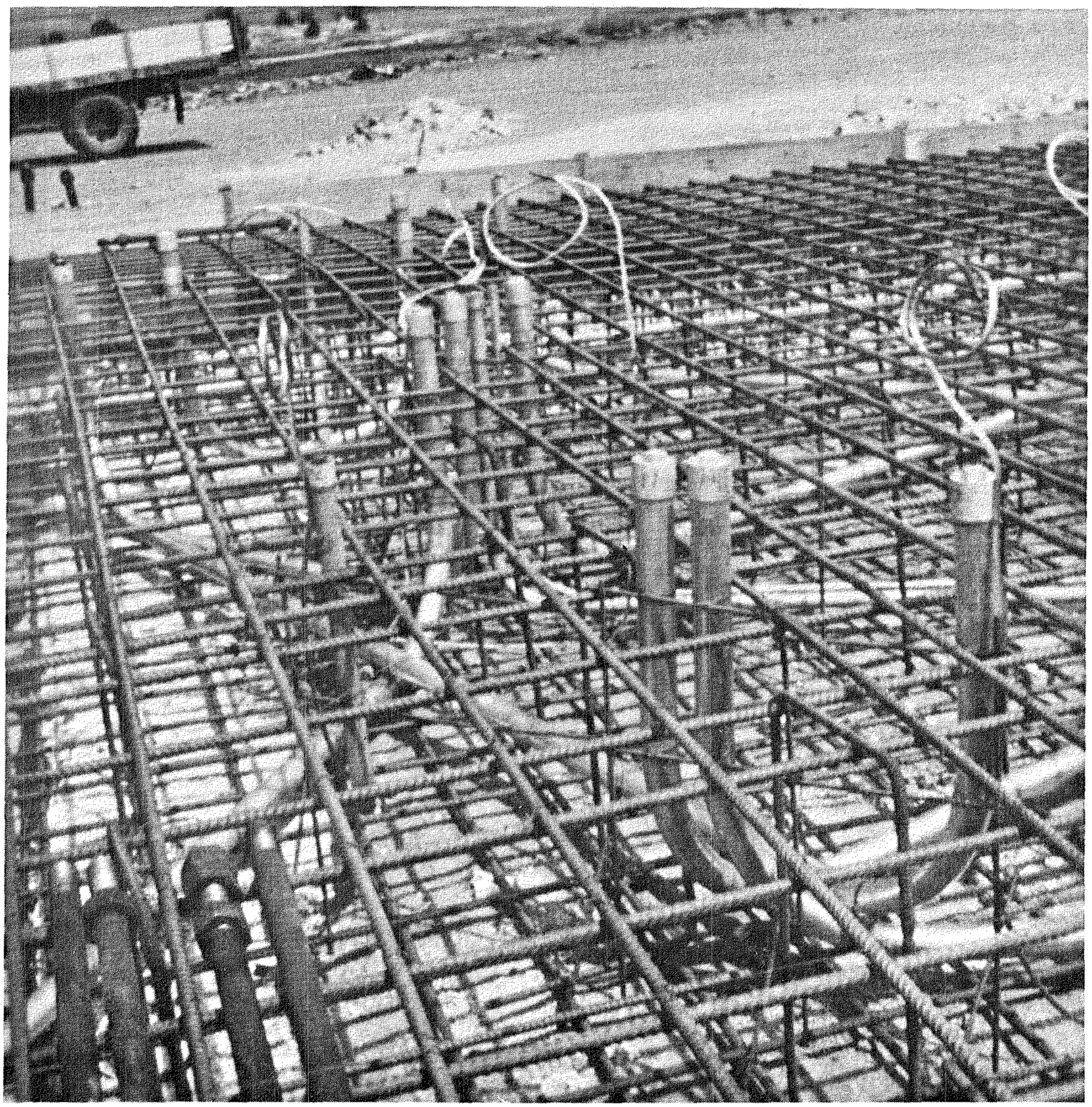

Figure 4.5.2-4. Mat Reinforcing Rods
(Before Concrete was poured)

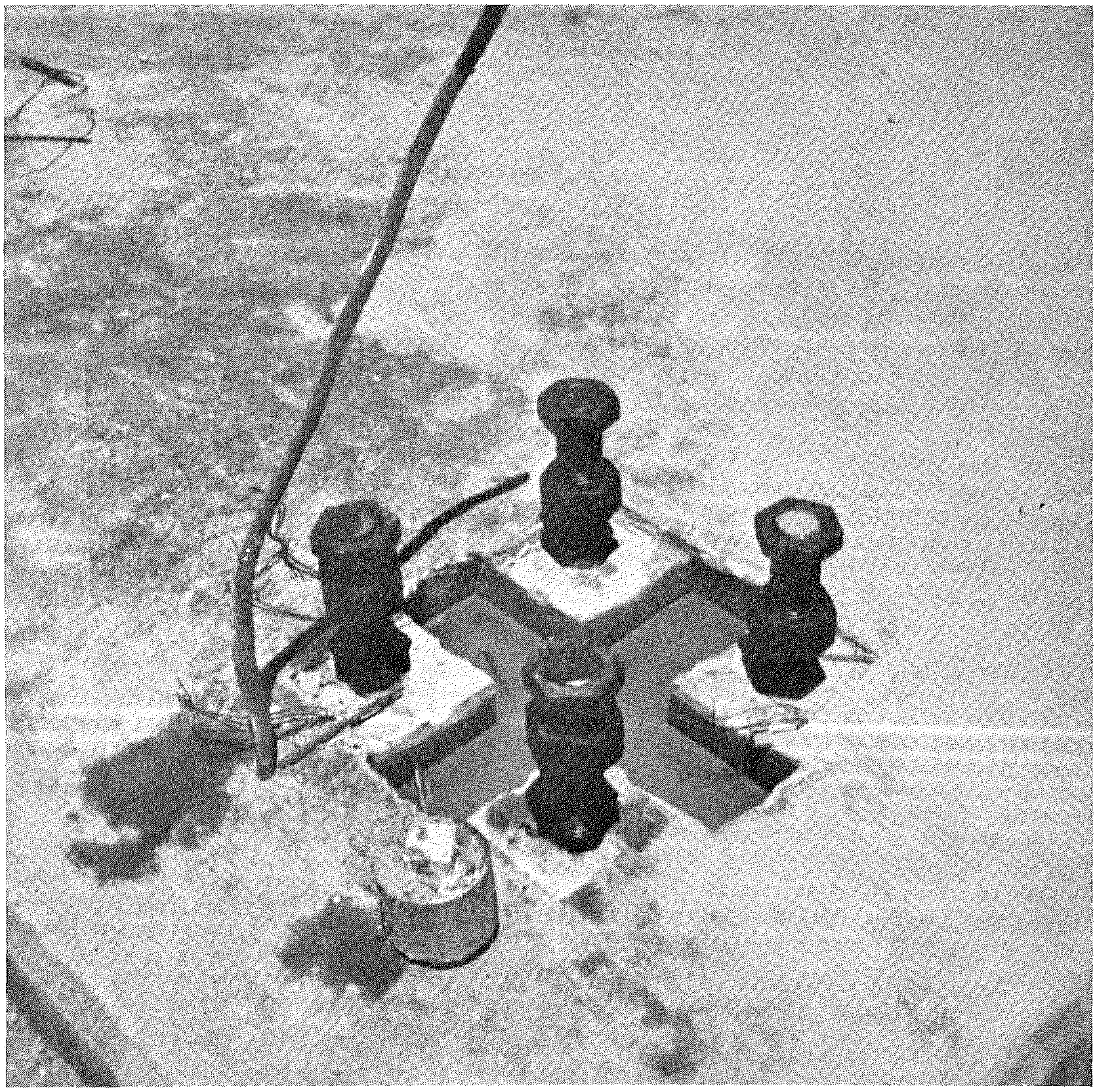

Figure 4.5.2-5. Tower Leg Mount on Completed Foundation

about 640 feet (195.0 m) and is buried approximately three feet (0.9 m) deep. Several parallel connections were provided to reduce the inductance for better lightning discharge. Also, to improve grounding as the grounding conductors passed through the foundation, connections were made to the reinforcing bars and the anchor bolts. The tower legs and control building base are grounded to the buried loops through the mounts to the rebar and then through ground wires to the ground loops.

4.5.2.4 SUPPORTING ANALYTICAL RESULTS

The design loading condition for the foundation is shown in Figure 4.5.2-6. The loads are produced by the dead weight of the tower and WTG components and by the worst case wind loads (due to a 150 mph or 67.0 m/s hurricane) on the tower and rotor. Figure 4.5.2-7 illustrates the foundation load points, the locations of mat positive and negative bending, and the mat/soil interface loads.

For the "side-on" wind, the calculated horizontal wind load on the tower, nacelle, and rotor is 68,000 lbs (302,000 N). The total weight, including foundation, is estimated to be about 784,000 lbs (355,600 kg). Since the coefficient of friction at the foundation/soil interface is expected to be well above 0.2 (giving 157,000 lb or 700,000 N friction force), there is ample margin against sliding. The maximum overturning moment due to the wind is 5,460,000 ft lbs (7,400,000 Nm). This produces a peak soil bearing pressure of 1570 lbs/ft^2 (75,200 Pa) which is well within the 4000 lbs/ft^2 (190,000 Pa) allowable. The restoring moment about the edge of the foundation due to the various component weights is 13,143,000 ft lbs (17,800,000 Nm) providing considerable margin against overturning. The factors of safety are: 2.3 against sliding and 2.4 against overturning. A similar analysis for the skewed wind indicates approximately 4000 lbs/ft^2 (190,000 Pa) peak bearing pressure at the corner of the foundation and factors of safety of 2.0 against sliding and 3.1 against overturning. These same assumptions were used to determine the foundation bending moments and to design the mat reinforcement.

Several studies were performed to determine the effect of non-rigid foundations on the vibration characteristics of the tower.[47] The basis for these evaluations was the fixed base tower first mode frequency. It was found that the change in natural frequency of the tower on a non-rigid foundation varies with the stiffness of the soil. For dense, well graded material or bedrock (E above 10,000 psi or 68.9 MPa) the foundation motion is small and can be ignored. For medium to dense sand (E = 7000 - 10,000 psi or 48.3-68.9 MPa) the percent change in first mode frequency ranges from 4 to 18 percent. For cohesive soil or loose sand (E 5000 psi or 35 MPa) the foundation effect is important and the change in frequency can be greater than 20 percent. Therefore, it was concluded that this mat foundation will function as a rigid base for the tower providing due care is taken in excavation and soil preparation.

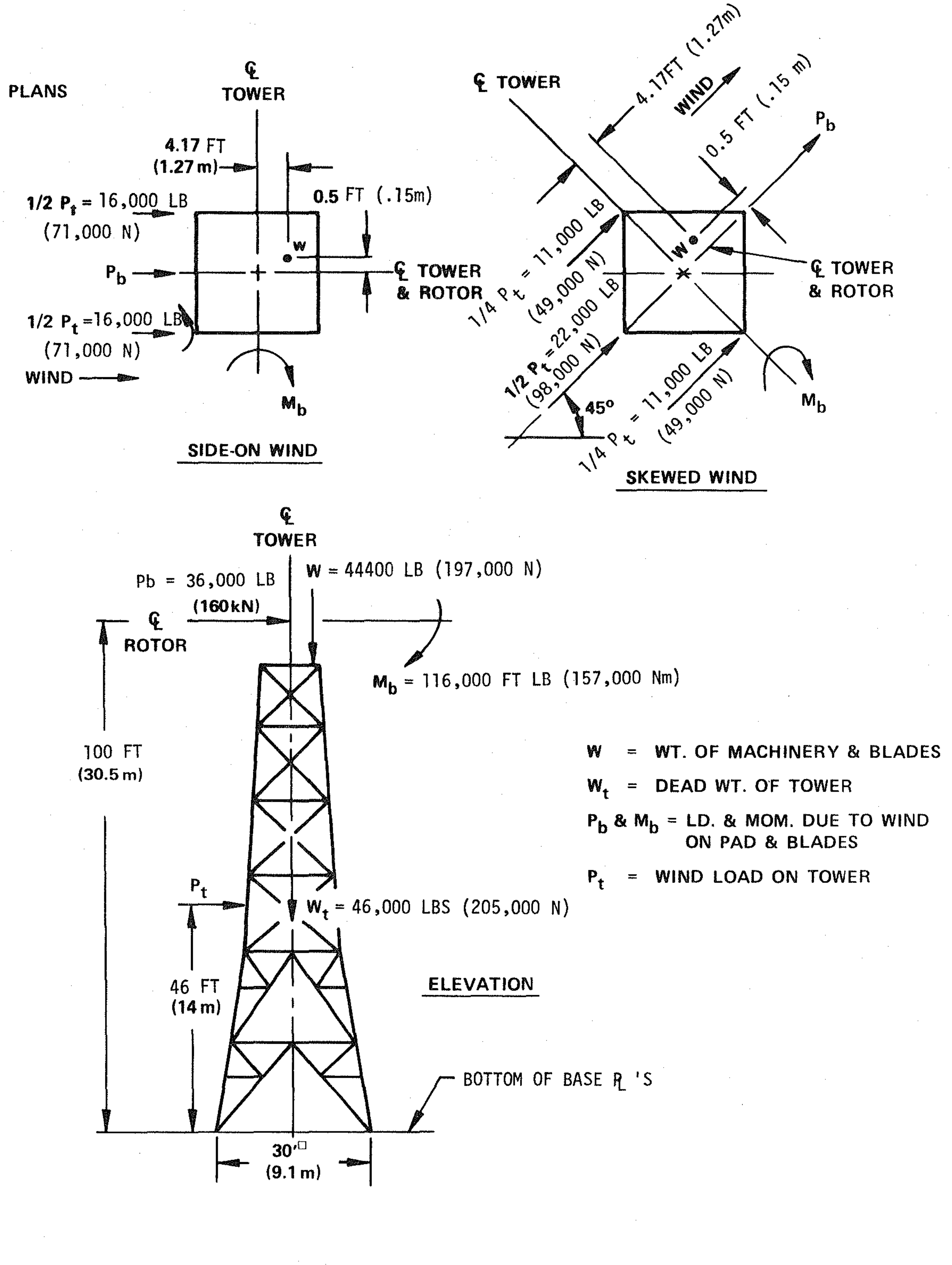

Figure 4.5.2-6. Design Loading Data (for foundation)

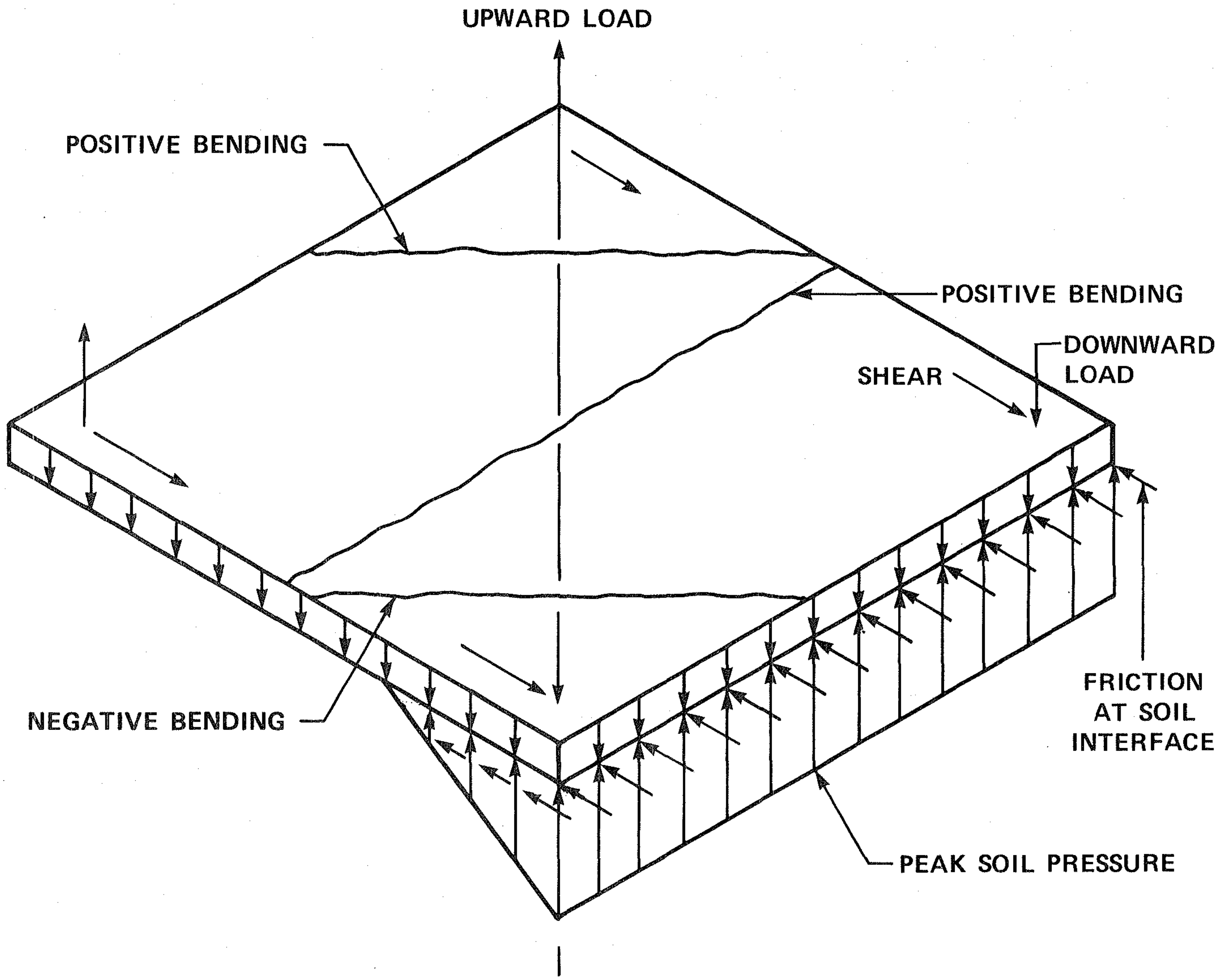

Figure 4.5.2-7. Wind Turbine Tower Foundation Load Schematic

4.5.3 SERVICE STAND

The service stand is a structure for supporting the wind turbine assembly when this assembly is not mounted on top of the tower. The stand is used during shop assembly and field installation of the machine. It is considered a permanent part of the installation at the site and is used each time the nacelle with its tower mounted equipment is lowered to the ground for servicing or repairs.

4.5.3.1 REQUIREMENTS

The service stand is required to interface properly with the tower mounted equipment and support the weight of this equipment in a safe manner. The weight of the equipment to be supported is 44,900 pounds (20367 Kg). The stand should be sized to be reasonably compact for ease of shipment.

The stand must be constructed for the safety of personnel working in the area. The requirements of the American Institute of Steel Construction (AISC) Specification for the Design, Fabrication and Erection of Structural Steel for buildings are to be satisfied. Bolts must be made from either ASTM A325 or A49 material. Welding must conform to the structural welding code of the American Welding Society, AWS D1.1-75. Cleaning prior to painting is to be done in accordance with the Surface Preparation Specification of the Steel Structure Painting Council.

4.5.3.2 DESIGN APPROACH

The service stand was designed using structural steel members that are easily obtainable in any large city. Welded construction was used to eliminate any maintenance problems with the stand.

4.5.3.3 SELECTED DESIGN

The design of the service stand is shown on NASA Dwg. No. CF760271 (W1015F85) and is pictured in Figure 4.3-1. It is an assembly of structural steel members that is 4 feet 9 inches (1.45 m) high, 8 feet (2.4 m) long and 8 feet (2.4 m) wide. W8 x 40 wide flange structural steel members conforming to ASTM A36 specification are used as support posts at each corner of the stand. These posts are the principle load carrying members of the stand.

Structural angles are used as diagonal braces to provide stability. The stand is primed with one coat of zinc chromate paint and finished with two coats of oil alkyd paint for corrosion protection.

At the construction site, a foundation for the service stand is provided at the base of the tower that can support the weights involved. Shim packs are provided as part of the service stand to help in providing a good interface fit between the service stand and the mounting frame.

4.5.4 EQUIPMENT AND PERSONNEL HOIST

A mechanical hoist is used instead of stairs to provide access to the top of the tower. It operates within the envelope of the tower.

4.5.4.1 REQUIREMENTS

The hoist must provide the capability of taking equipment and personnel to the top of the tower for various reasons such as maintenance. In doing this the hoist must satisfy the following requirements:

Capacity	1500 pounds (680 kg)
Rating	Personnel (4) or Freight
Drive	Self-Powered by Electric Motors
Location	Within Framework of Tower
Height of Travel	74 feet (22.6 m)
Environment	Outdoors
Safety	Per Spec ANSI A121.1-1970
Speed	35 feet per minute (0.178 m/s)

4.5.4.2 DESIGN APPROACH

Operation of the MOD-0 machine indicated that the wind shadow created by the tower and by the steps on the tower was detrimental to the operation of the machine. The MOD-OA WTG, therefore, was designed with an electric operated hoist in lieu of steps. The hoist was to provide a safe and effective method of providing manned access to the top of the tower so that maintenance work could be done expeditiously. A commercial hoist unit with proven capabilities and safety of operation was selected to minimize development problems and cost.

4.5.4.3 SELECTED DESIGN

The equipment and personnel hoist is a commercial model (ST-27 Shafter) manufactured by the Spider Staging Sales Company, Renton, Washington. This hoisting unit is shown in Figure 4.5.4-1. The unit is installed within the framework of the tower and ascends vertically from grade to a landing located about 74 feet (22.6 m) above grade. Hoisting, safety, and guide cables are hung from a beam provided for each purpose at about 81 feet (24.7 m) above grade. The bottom end of the safety and guide cables are anchored to a concrete foundation at the base of the tower. The platform and its control and safety devices are continuously exposed to the weather. Motors and all electrical control and safety devices are constructed or protected in such a way that exposure to the weather will not interfere with their proper operation. Design, construction and installation of the platform conforms with all the requirements of Parts II and III of the American National Standard Safety Requirements for Powered Platform for Exterior Building Maintenance, ANSI A120.1-1970 Specification.

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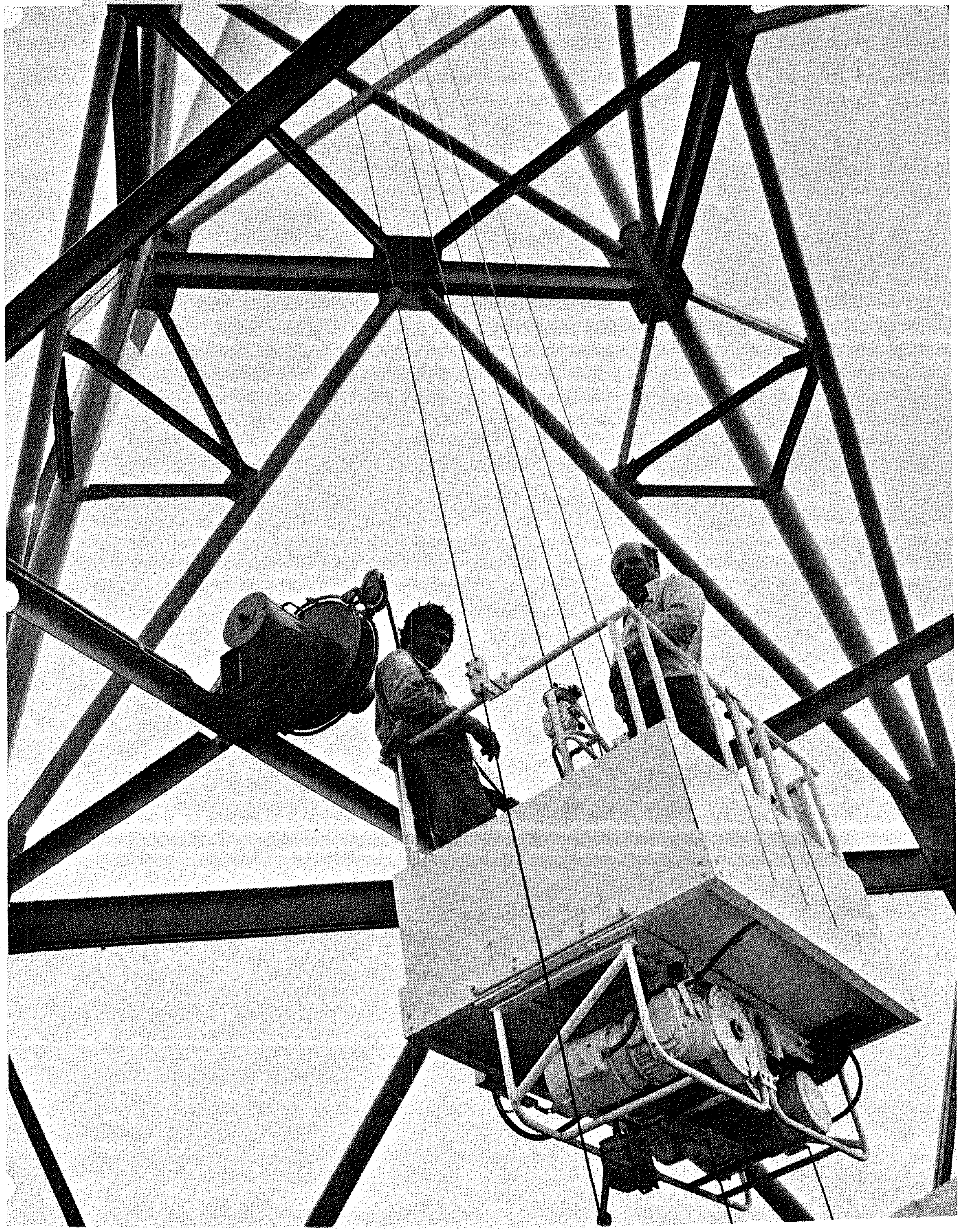

Figure 4.5.4-1. Equipment and Personnel Hoist

Characteristics and features of the design are as follows:

(a) Size: 48 inches (121.9 cm) wide by 60 inches (152.4 cm) long by 75 inches (190.5 cm) high.

(b) Rated load (gross): Not less than 1500 pounds (680.4 kg). Minimum pay load is 850 pounds (385.6 kg). A noncorrosive plate stating the maximum permissible rated load is posted on the platform.

(c) Speed: 35 feet per minute (0.178 m/s), ascending or descending.

(d) Hoisting Ropes: Two 5/16 inch (0.79 cm) diameter stainless steel ropes of 6 x 19 or 6 x 37 construction fitted with swaged-on drum hooks and a thimble eye splice. Breaking strength of each rope is at least 20,500 pounds (91.2 kN). Ropes are long enough to permit at least three turns to remain on each winding drum when the platform is at the lowest point of travel.

(e) Hoisting Machinery: Two power driven winch drums contained on the underside of the platform.

(f) Drive: Two one-hp (746 W) minimum, 208 V, three phase, heavy-duty electric motors directly connected to the hoisting machinery.

(g) Brakes: Solenoid actuated primary brakes on each worm gear shaft; when power is off, brake is on. Automatic, inertia-operated emergency brake on each drum. Each brake system shall be designed to stop and hold the platform with 125 percent of rated load.

(h) Fail Safe Rope Grip: Designed and constructed to prevent the platform from falling to the ground if the hoisting cables or brakes should fail.

(i) Safety Railing: Two continuous non-removable, welded, aluminum alloy rails. Top rail is 42 inches (106.7 cm) above floor of platform and the intermediate rail approximately midway between the top rail and the floor.

(j) Toeboard: Continuous around all four sides of the platform and extending at least four inches (10.2 cm) above floor level.

(k) Skirt: Spaces between the intermediate safety rail and the toeboard are filled with metallic mesh or similar material that will reject a ball one inch (2.54 cm) in diameter. The installed mesh shall be capable of withstanding a load of 100 pounds (444.8 N) applied horizontally over any area of 12 square inches ($7.74 \times 10^{-3} m^2$).

(l) Access Gate: Located at center of long side of platform. The gate permits access without stepping over any obstructions extending above the floor level, and is self-closing and self-locking. The gate does not protrude beyond the plan dimensions of the platform when open.

(m) All aluminum and steel surfaces are primed and painted with two finish coats of white machinery enamel.

(n) Safety Rope: A 5/16 inch (0.79 cm) diameter steel safety rope extends from grade to about 81 feet (24.7 m) above grade and passes through the "fall safe" rope grip on the platform. The rope is the same as the hoisting ropes and has a thimble eye splice at the top end and a loop with thimble and three rope clips at the bottom end. A turnbuckle for tension adjustment is included.

(o) Guide Cables: Two 1/4 inch (0.64 cm) diameter stainless steel cables are used to provide stability to the hoist. They extend from grade to 81 feet (24.7 m) above grade and pass through stationary guide devices at the center of the short sides of the platform. One cable is positioned at each side and each cable passes through two guides. The cables have a thimble eye splice at the top end, a loop with thimble and three rope clips at the bottom end, and a turnbuckle for tension adjustment.

Electrical equipment and wiring conforms to the requirements of the American National Standard National Electric Code, C1-1968. All motors and control equipment are supplied from a single power source of 120/208 V, three phase, four wires plus ground wire. The power supply for the platform is an independent circuit supplied through a fused disconnect switch available at a terminal box at the base of the tower or at the 85-foot (25.9 m) level. Electrical conductor parts of the power supply system are protected from accidental contact for safety reasons. Three operating control stations are provided; one on the traveling platform, one push-button station at grade, and one push- button station at the landing 74 feet (22.6 m) above grade. The three stations are electrically interlocked such that the platform station always over-rides the two remote stations. Provision for electrical grounding is a feature of the power supply system. The platform and noncurrent carrying parts of electrical equipment are grounded through a grounding connection in a traveling cable. An automatic rewind cable reel with guide roller outlet and power and control cables is installed on the support tower at about 21 feet (6.4 m) above grade. Cable is Type 50, suitable for outdoor service.

Safety Devices

- An electric contact is provided and so connected that it will cause the UP direction relay for vertical travel to open if tension in the traveling power cable exceeds safe limits.

- An automatic overload device is provided to shut off the power to the circuit of both hoisting motors for travel in the UP direction should the load applied to either hoisting rope exceed 125 percent of its normal tension with rated load.

- An upper directional limit device prevents the travel of the platform beyond the normal upper limit of travel. Operation of the directional limit device prevents further motion in the upward direction of travel.

4.6 ELECTRICAL SYSTEM AND COMPONENTS

The MOD-OA wind turbine electrical power system consists of the generator, slip rings, switchgear, interfacing transformer, and the oil circuit recloser. Figure 2.9-1, previously discussed, illustrates the essential components of the electrical system.

4.6.1 GENERATOR

The energy of the wind imparted to the blades and the drive train is converted to electrical energy by the generator.

4.6.1.1 GENERATOR REQUIREMENTS

The generator for the MOD-OA wind turbine is required to convert the mechanical energy of the wind to electrical energy in accordance with the mechanical parameters on the drive train side and the electrical parameters on the output side. The overall system design dictates that the generator be rated 250 kVA continuous, 0.8 power factor with a minimum efficiency of ninety percent. Since the blades and low speed shaft operate at a nominal 40 rpm, which translates to 1800 rpm at the high speed shaft, the generator rotor operates at 1800 rpm. The electrical output of the generator must be 480 V, three phase, 60 Hz, grounded wye making it compatible with the switchgear. The exciter is a directly connected brushless type to provide simplicity and high efficiency. Since the generator is located within the nacelle the generator requires a drip proof enclosure. Due to the operating environment the generator insulation must be class B for 40°C ambient and 70°C rise. To minimize the components located in the nacelle and simplify the system design the generator must be self-cooled. In order to perform dynamic testing on the drive train, the generator must be capable of operating in the motoring mode and accelerate the drive train.

4.6.1.2 APPROACH

The original basis for the selection of a constant speed generator in the MOD-0 system was the availability of time tested, off-the-shelf equipment which makes for economical generation of electrical power. Initially, the MOD-OA system was conceived as a stand alone system with the potential for remote installation.

Stand alone capability ruled out the use of an induction generator without the installation of a backup supply. A synchronous generator was therefore selected since it met the requirements and was commercially available as a standard component. The generator complies with NEMA Standards Publication MG1 as it relates to generators.

4.6.1.3 SELECTED DESIGN

The generator selected for MOD-OA is a Kato Engineering Model 200EU9E synchronous generator. As shown in Figure 4.6.1-1, the generator includes an integral terminal box in which the power and field connections are made. Figure 4.6.1-2 is a cutaway view of the generator showing the arrangement of

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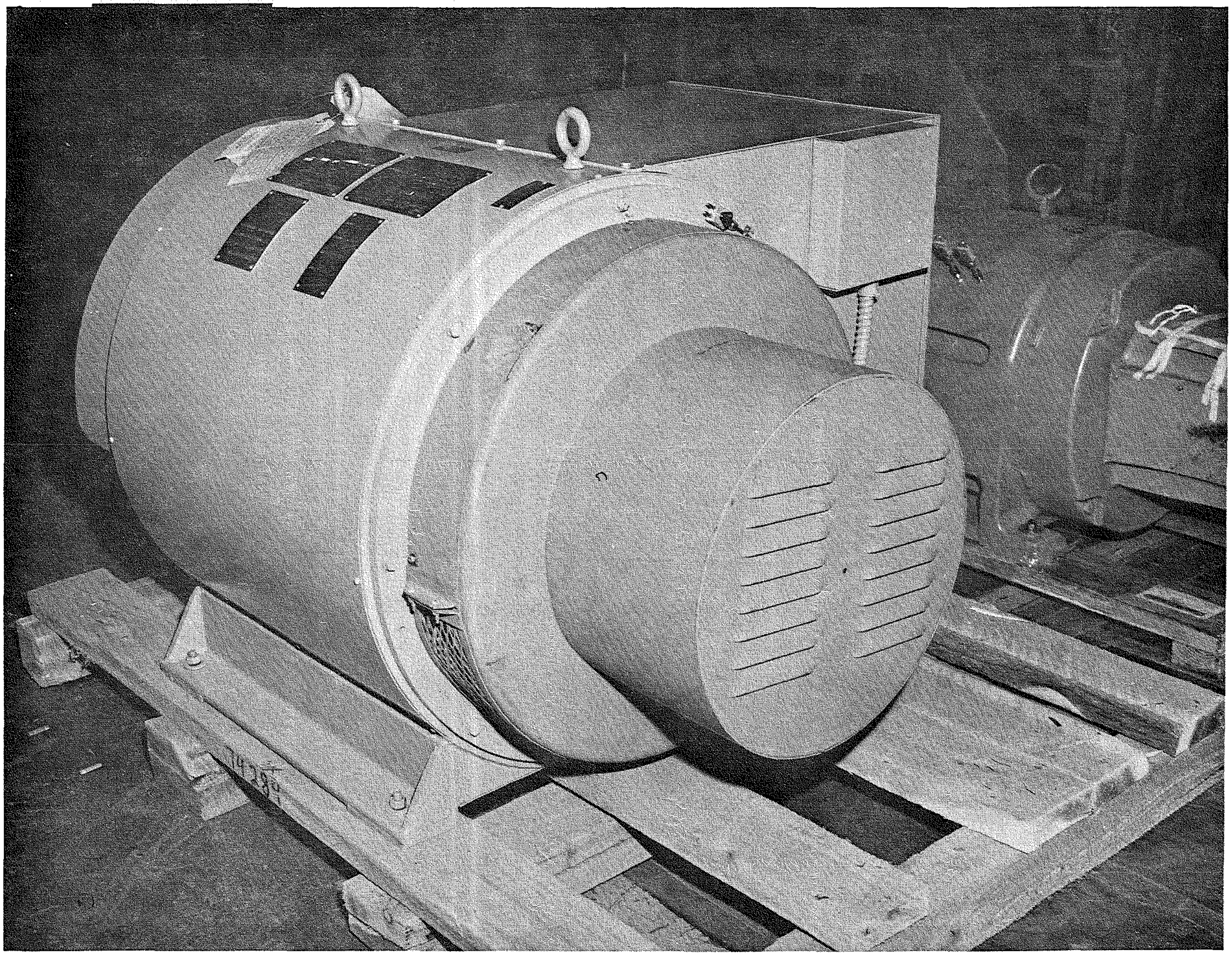

Figure 4.6.1-1. MOD-OA Generator

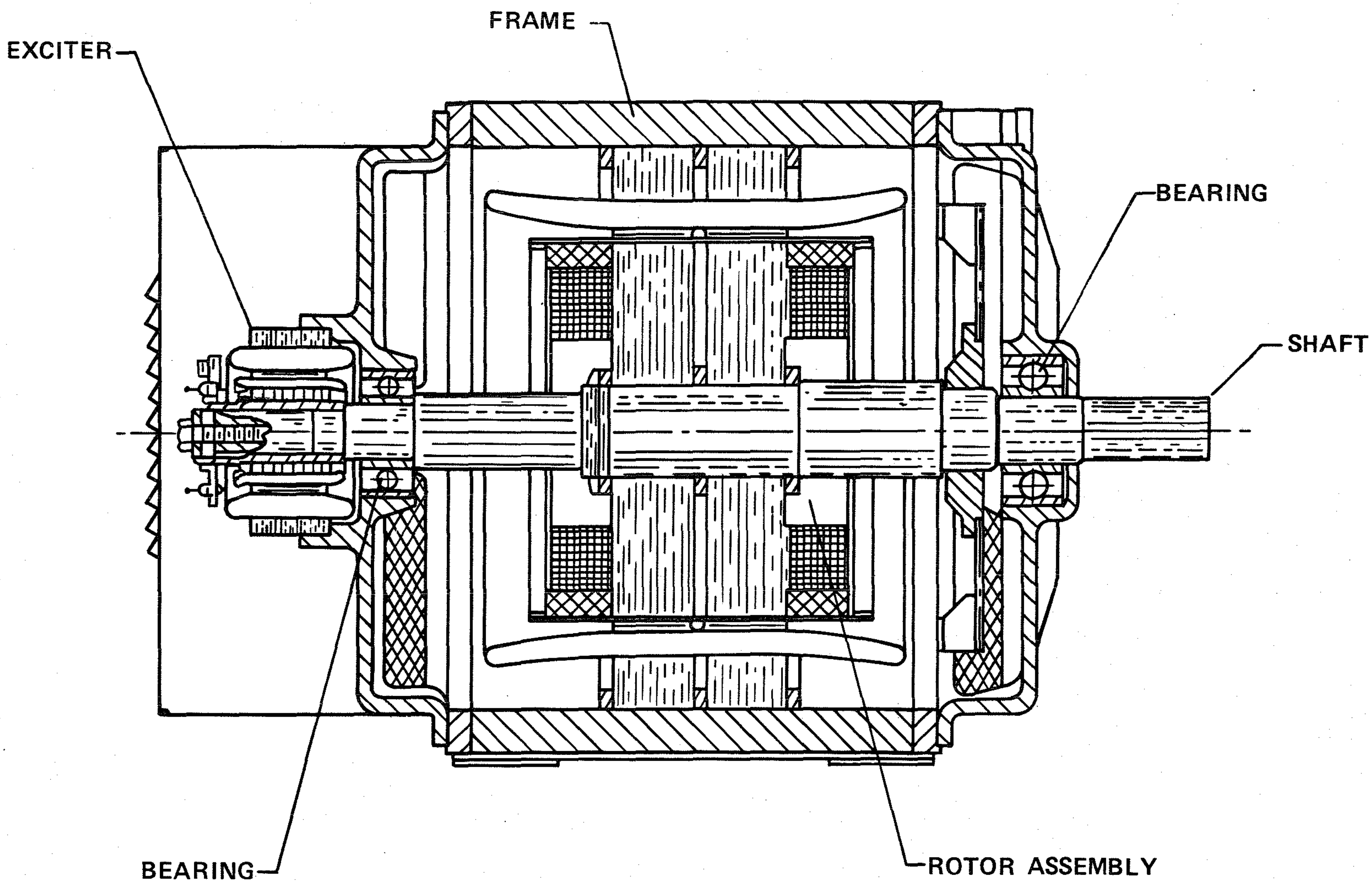

Figure 4.6.1-2. MOD-OA Generator

generator components. The design includes two sets of prepacked rolling element bearings and is capable of accelerating a load inertia of 20 pound-feet-second^2 (27.1 Nms^2) without overheating. The electrical characteristics of the generator are presented in Table 4.6.1-1.

4.6.1.4 SUPPORTING ANALYTICAL RESULTS

An analysis of the dynamic behavior expected from the MOD-OA wind turbine generator, when operated in parallel with an isolated diesel electric power system, is presented in Power Technologies Report Number R-42-77: "Wind Turbine Operation In Parallel to Diesel Generation".[48] The primary objective of the study was to model the MOD-OA machine and a utility system representative of those at Clayton and Culebra Island to develop an understanding of the circumstances, if any, under which detrimental dynamic interaction could occur. A secondary objective of the study was the examination of the wind turbine governor in both the speed and power control modes to ensure that changeover between modes can be achieved in a satisfactory manner without detrimental effect on the utility system.

The results of the above referenced report consisted of a series of simulation response plots. Examination of these plots showed the effect of various wind machine design and system operation options on the magnitude of the power pulsations produced by the wind machine and on the transients involved in changing from one control mode to the other.

4.6.2 SWITCHGEAR

Electric power produced by the wind turbine generator is transmitted from the generator in the nacelle, through a set of slip rings to a cable, to the base of the tower. At the tower base the power cable is routed to the switchgear located in the control building. The switchgear incorporates those devices and components required to control and protect the generator, synchronize the WTG to the utility network and provide the parasitic power requirements of the WTG.

4.6.2.1 SWITCHGEAR REQUIREMENTS

The switchgear is typical of indoor, metal enclosed, low voltage, distribution switchgear suitable for service on a nominal 480 V, 325 kVA, three phase, four wire, grounded neutral, 60 Hertz system. Fault current available at the switchgear dictates that the switchgear be constructed to withstand a fault current of 22 kA rms symmetrical at 480 V. The nominal rating of the bus is 600 A, 480 V. Figure 4.6.2-1 shows the one line diagram of the MOD-OA power system including the switchgear.

The switchgear consists of a dead front type, metal enclosed, self supporting structure with three compartments to accommodate the switching and protective devices arranged as shown in Figure 4.6.2-2. Each compartment includes a dead front hinged cover. Provisions are made for the installation of all interfacing power and control cables through the bottom of the switchgear structure. The bus bar is mounted on high impact, non-tracking, insulated supports and braced to withstand the mechanical forces exerted by a fault current of 22 kA rms symmetrical at 480 V.

TABLE 4.6.1-1: GENERATOR ELECTRICAL CHARACTERISTICS

Kato Generator Model 200EU95

Base KVA	250 kVA
Base Voltage	480 V
Base Frequency	60 Hz
Power Factor	0.8
Configuration	4 wire, grounded wye
Number of Poles	4 Poles
Xd Unsaturated Direct Axis Synchronous Reactance	1.80693 per unit
Xq Unsaturated Quadrature Axis Synchronous Reactance	1.06988 per unit
X'd Direct Axis Transient Reactance - Unsaturated	0.28396 per unit
Saturated	0.24989 per unit
X"d Unsaturated Direct Axis Subtransient Reactance	0.12849 per unit
X"q Unsaturated Quadrature Axis Subtransient Reactance	0.09418 per unit
X_2 Negative Sequence Reactance	0.11133 per unit
X_0 Zero Sequence Reactance	0.05854 per unit
X_1 Leakage Reactance	0.06729 per unit
T'do Direct Axis Transient Open Circuit Time Constant	2.605 seconds
T'd Direct Axis Transient Short Circuit Time Constant	0.360 seconds
T'qo Quadrature Axis Subtransient Open Circuit Time Constant	0.025 seconds
r_a Armature Resistance	0.01275 /phase

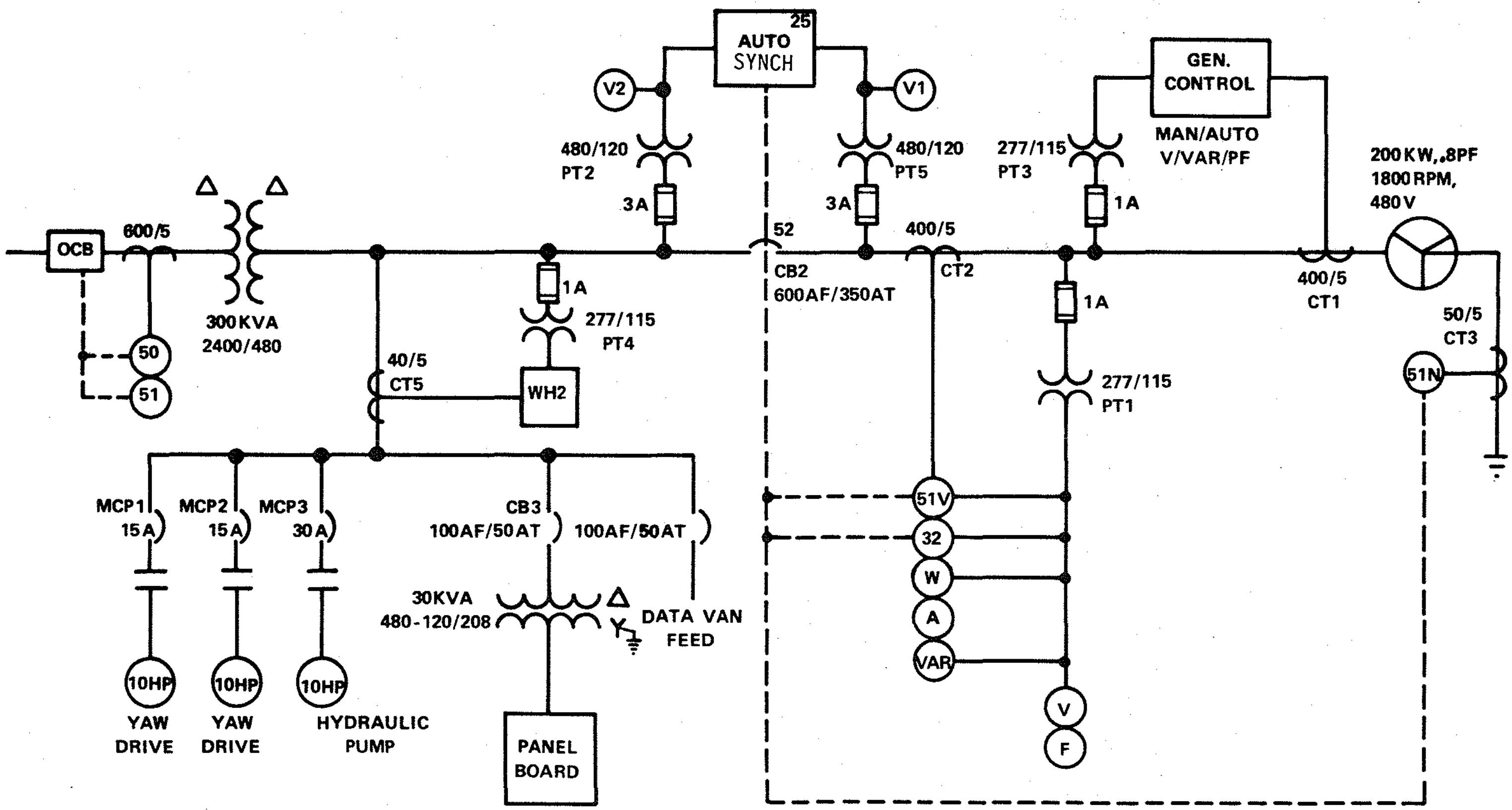

Figure 4.6.2-1. MOD-OA Power System One-Line Diagram

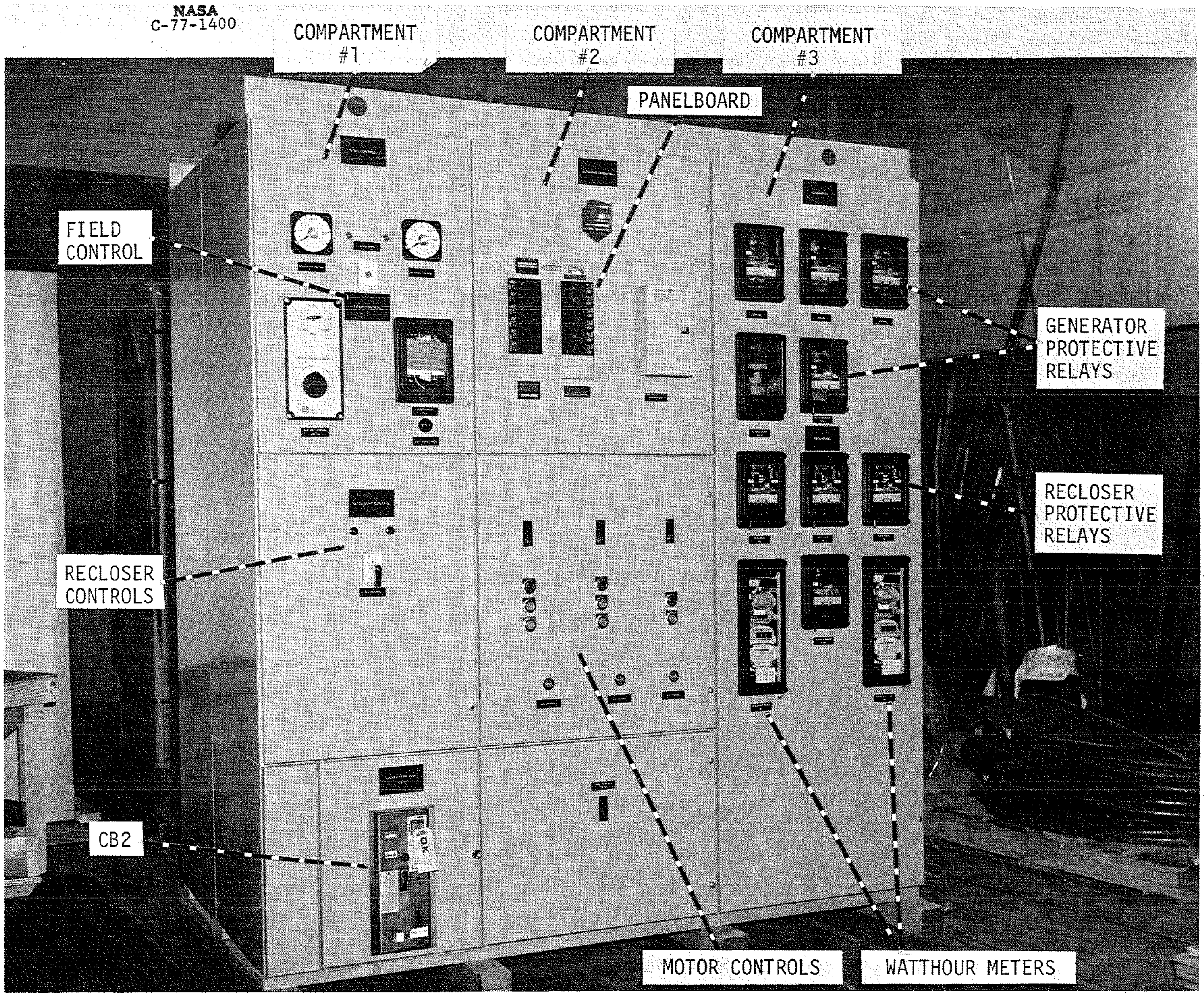

Figure 4.6.2-2. MOD-OA Switchgear

The circuit breaker designated as CB2 on Figure 4.6.2-1 is required to provide a tie between the WTG and the utility network. The breaker controls must provide for closing of the breaker when the utility network and the WTG are synchronized as well as manual closing as required. The synchronizing device (device number 25) receives input from potential transformers located on the utility and WTG sides of the tie breaker. When the two systems are in synchronization, the synchronizing device instructs the tie breaker to close thus tying the systems together. Voltmeters display the input voltages to the synchronizing device.

The tie breaker is required to trip manually, on overcurrent, on reverse power or on generator neutral overcurrent. Overcurrent voltage restraint relays (device number 51V) which sense the current and voltage on the generator side of the breaker are required to provide system fault backup protection at the generator since it is a source of fault current. These devices protect against the generator continuing to supply short-circuit current to a fault in the utility network if the fault is not removed by other protective equipment. A reverse power relay (device number 32) which senses the direction of power flow is required to protect the generator from motoring conditions under which power would flow to the generator rather than from the generator. A time overcurrent relay (device number 51N) is required to sense current flow in the generator neutral and trip the breaker when the neutral current is of a magnitude and duration indicative of a generator fault.

Instrumentation to sense power, current, VARS, voltage and frequency at the bus is required to provide electrical operating data for the WTG system. These devices are located in the switchgear and receive their inputs from the same current and potential transformers utilized for the relaying scheme.

Controls for the generator are located in the switchgear and provide for manual, automatic, voltage, VAR and power factor control of the generator. Details of the generator controls are presented in Section 4.7.3. The current and potential transformers associated with the generator controls are located on the generator side of the switchgear bus.

Instantaneous and time overcurrent relays (device numbers 50 and 51) as well as the manual controls associated with the oil circuit recloser are located in the switchgear. Details of these devices are presented in Section 4.6.3.

The switchgear must provide for the parasitic power requirements of the WTG system which include two ten horsepower (7.46 kW) yaw drive motors, a single ten horsepower (7.46 kW) hydraulic pump motor, a stepdown transformer and a panelboard to provide 120/208 V power and lighting circuits and a 480 V, three phase feed to the data van. The motors for the yaw drive system require individual combination startup which include circuit breakers and motor starters rated 480 V, full voltage reversing, NEMA size 0, three pole with magnetic trip. The hydraulic pump motor requires a single nonreversing combination starter rated 480 V, full voltage starting, NEMA size 1, three pole with magnetic trip.

The power and lighting load requires a 30 kVA, three phase, 480 V primary, 120/208 V secondary stepdown transformer. The transformer is protected on the primary side by a suitably sized molded case circuit breaker. The panelboard includes twelve 240 V molded case circuit breakers with ten kA rms symmetrical interrupting ratings with the number of poles and current ratings identified on NASA Dwg. No. CF758971 (W1016F02).

4.6.2.2 APPROACH

The switchgear design follows conventional utility practices for generator protection and synchronization of a generator to a utility network. The extent and cost of generator electrical protection are limited by the cost of the generator itself. Components and construction of the switchgear comply with NEC, NEMA, ANSI, IEEE codes and standards and utilize "off-the-shelf" components where feasible. Selection of components was based upon protection, availability and reliability so as to provide for unattended operation/protection of the WTG with a high degree of switchgear availability.

4.6.2.3 SELECTED DESIGN

As illustrated in Figure 4.6.2-2 the switchgear consists of three distinct compartments. The details of the selected switchgear components will be discussed on a compartment by compartment basis. Details of the wiring of the switchgear components is provided on NASA Dwg. Nos. CF759035, CF759036, CF759037, CF759038 and CF759039 (W1016F20).

COMPARTMENT NUMBER 1

Tie breaker CB2 is an Allis-Chalmers Model LA-600 power circuit breaker suitable for indoor operation. The breaker is of drawout construction, electrically operated with a voltage rating of 600 V. The breaker frame is rated for 600 A with a 350-ampere trip setting and designed for three phase, 60 Hz, 22 kA rms symmetrical short circuit interrupting duty. The tripping device consists of a three element unit incorporating long time, short time and instantaneous tripping. The breaker is motor operated with stored energy (spring) closing and utilizes 48 VDC close and trip control.

Three current transformers designated CT2 are located on each phase of the bus on the generator side of the tie breaker. The CT's provide input to the relaying and monitoring scheme associated with the tie breaker and the generator. The CT's are Abbott Magnetics model 110-401, 400/5 ampere ratio, 600 V, class T-50, window type construction.

A pistol grip control switch provides manual control for the oil circuit recloser. The switch is a Westinghouse model 505A713G01 W-2 with a pistol grip handle incorporating trip, close and neutral positions. Red and green indicating lights are located adjacent to the switch to indicate close and trip status of the recloser.

Two Kratos model AAV.020 voltmeters with 0 to 150 V movements and 0-600 V scales provide indications of the voltage inputs to the synchronizing device.

The controls associated with the generator and synchronizer are located in this switchgear compartment, however their details are presented in Section 4.7.3.

COMPARTMENT NUMBER 2

Circuit breaker CB3 which protects the stepdown transformer is of molded case construction with 100 ampere frame and 50 ampere thermal magnetic trip. The breaker is rated at 600 V and 22 kA rms symmetrical interrupting capacity.

Motor starters number 1 and 2 (MS1, MS2) which control the yaw drive motors each consist of a Westinghouse model A210MOCAC motor starter and a model MCP03150R motor circuit protector. The motor starter is a full voltage reversing starter rated at 480 V, NEMA size 0, three pole, 60 Hz. The control coil is 120 VAC and the starter includes three thermal overloads. The motor circuit protectors provide magnetic tripping with a continuous current rating of 15 amperes and an adjustable trip range of 50 to 150 amperes for starting currents. The motor circuit protectors have an interrupting capacity of 14 kA rms symmetrical at 480 V.

Motor starter number 3 (MS3) which controls the hydraulic pump motor consists of a Westinghouse model A200M1CAC motor starter and a model MCP 13300R motor circuit protector. The motor starter is a full voltage nonreversing starter rated at 480 V, NEMA size 1, three pole, 60 Hz. The control coil is 120 VAC and the starter includes three thermal overloads. The motor circuit protector provides magnetic tripping with a continuous current rating of 30 A and an adjustable trip range of 100 to 300 A for starting currents. The motor circuit protector has an interrupting capacity of 14 KA rms symmetrical at 480 V.

Circuit breaker CB3 provides protection for the stepdown transformer and is of molded case construction with a 100 A frame, 50 A trip. An identical breaker is located in compartment number 2 which feeds the data van.

The power and lighting load is supplied from an Abbott WFB panelboard, 250VAC, 16 circuit, three Phase, four wire, 100 A bus. Westinghouse type BA circuit breakers with ten kA rms symmetrical interrupting ratings are installed in the panelboard. The individual full load current ratings, number of poles and loads served by the panelboard are identified on NASA Dwg. No. CF759035, CF759036, CF759037, CF759038 and CF759039 (W1016F20).

COMPARTMENT NUMBER 3

A single current transformer designated CT3 is located in the neutral of the generator. The CT provides input to the 5IN device which trips the tie breaker on excessive neutral current. The CT is an Abbott Magnetics model 100-500, 50/5 ampere ratio, 600 V, class T-50, window type construction.

Three current transformers designated CT5 are located on each phase of the bus which supplies the parasitic load requirements of the WTG. The CT's provide input to watthour meter WH2 which monitors the parasitic energy consumption. The CT's are General Electric type JKM-0 model 750X41G3, 20/50 ampere ratio, 600 V, class T-50, bar type construction.

Three potential transformers designated PT1 are located between each phase and neutral of the bus on the generator side of the tie breaker. The PT's provide input to the relaying and monitoring scheme associated with the tie breaker and the generator. The PT's are Abbott Magnetics model 450-288, 277 volt primary, 115 V secondary with an accuracy of 0.3.

Potential transformers designated PT2 and PT5 are located between two phases of the switchgear bus on the utility and generator sides of the tie breaker respectively. The PT's provide phase angle and frequency input to the automatic synchronizing device which monitors these parameters and allows the tie breaker to close when the utility and generator are synchronized. The PT's are Abbott Magnetics model 450-288. 480 V primary, 120 V secondary with an accuracy of 0.3.

Potential transformer PT3 is located between one phase and neutral of the bus on the generator side of the tie breaker. The PT provides input to the manual voltage control module when the field contractor is closed. The PT is an Abbott Magnetics model 450-288, 277 V primary, 115 V secondary with an accuracy of 0.3.

Potential transformers designateo PT4 are located on each phase of the switchgear bus on the utility side of the tie breaker in an ungrounded wye configuration. The PT's provide input to watthour meter WH2 which monitors the parasitic energy consumption of the WTG. The PT's are Abbott Magnetics model 450-288, 277 V primary, 115 V secondary with an accuracy of 0.3.

Overcurrent voltage restraint relays designated OCVR1, OCVR2 and OCVR3 receive current inputs from CT2 and voltage inputs from PT1 to sense generator output parameters. The relays protect against the generator continuing to supply short-circuit current to a fault in the utility network if the fault is not removed by other protective equipment. The relays are General Electric type IJCV51A9A time overcurrent relays, single phase, voltage restraint, 60 Hz, inverse time characteristics, 208 V, 4 to 16 A range. Loss of potential to the relays will cause the relay to trip if the generator load current, expressed in relay secondary amperes, is greater than the zero voltage pickup current of the relay.

Reverse power relay RPR1 receives single phase current and voltage input associated with the generator. The relay is a Westinghouse type CRN-1 model 190B038A11 directionally controlled timing relay used to protect the generator from motoring. When a power reversal condition occurs and persists for a predetermined time interval the relay will trip tie breaker CB2. The relay is rated for 208 Volt .020 amperes pickup. The low input current of the relay requires an additional current transformer in the secondary circuit of CT2 with a 5/0.2 ampere ratio.

Time overcurrent relay 1-51N receives input from current transformer CT3 located in the generator neutral. The relay protects against generator faults to neutral by tripping tie breaker CB2 on excessive neutral current. The relay is a General Electric type 12IAC53A801A time overcurrent relay, single phase, 60 Hz, very inverse, 0.5 to 4 ampere range.

Instantaneous and time overcurrent relays 50/51 receive input from the bushing type current transformer located on each phase of the oil circuit recloser.

The relays trip the oil circuit recloser on instantaneous and time overcurrents. The relays are General Electric type 12IAC51B806A time-overcurrent relays with an instantaneous trip unit. The devices are single phase, 60 Hz, with a moderately inverse range of 2 to 16 amperes and an instantaneous range of 10 to 80 amperes.

The parasitic power and lighting load is supplied by an MGM Transformer Corporation lighting transformer. The transformer is three phase, 30 kVA, 480 primary, 120/208 V secondary. The unit is of dry type construction and incorporates two 2-1/2% taps above and below rated voltage.

Watthour meter WH1 measures the energy output of the generator based on input provided by PT1 and CT2. The meter is rated 120 V, 2.5 ampere, three stator cyclometer register for use with three - 400/5A CT's and three - 277/115V PT's connected phase to neutral on a three phase, four wire, 60 Hz system and includes a pulse generator rated for 120 V, 10 kWH (3.6×10^{10} joules) per pulse.

Watthour meter WH2 measures the energy consumed by the parasitic load based on input provided by PT4 and CT5. The meter is rated 120 V, 2.5 A, three stator cyclometer register for use with three - 20/5A CT's and three - 277/115V PT's connected phase to neutral on a three phase, four wire, 60 Hz system and includes a pulse generator rated for 120 V, 100 kWh (3.6×10^{11} joules) per pulse.

Instrumentation which senses power, current, VARS, voltage and frequency at the generator bus are located in compartment 3 of the switchgear however the details of these components are provided in Section 8.1.5 of this report.

4.6.2.4 SUPPORTING ANALYTICAL RESULTS

Techniques for evaluating unbalanced short-circuit faults in wind turbine systems are presented in Reference 49. Four different types of faults are discussed. For each case, complete solutions for armature, field, and damper circuit currents; short circuit torque and open phase voltage are derived by mathematical analysis.

The analytical study concludes the following:

1. Severe electrical transients resulting from short-circuit faults associated with the generator can be effectively reduced by the neutral to ground impedance of the generator.

2. Protection of wind turbine systems from transients resulting from line to line and simultaneous faults must be provided by circuit breakers or fuses at the generator output.

3. For all WTG systems short circuits should be analyzed and the effects of faults on the overall system be taken into consideration in the design of control and protective subsystems including switchgear components.

4.6.3 TRANSFORMER AND UTILITY CONNECTION

Electric power produced by the wind turbine generator must be transformed to make the output voltage compatible with the network voltage of the interfacing utility.

4.6.3.1 REQUIREMENTS

The voltage at the WTG switchgear is 480 V, three phase, four wire, grounded wye while that of the interfacing utility network is 2400 V, three phase, three wire, delta. A transformer sized to accommodate the output of the WTG and accommodate the connections of the interfacing systems is required. Due to space limitations in the control building the transformer must be suitable for outdoor operation in a padmountable configuration. The transformer must be protected from fault conditions associated with the utility side and the WTG side of the transformer. The protective device must be of three phase construction to prevent the generator from operating in the single phase mode and provide a convenient means of isolating the WTG system for maintenance purposes. Like the transformer the protective device must be suitable for outdoor operation and assume a padmount configuration to maintain a low profile and facilitate maintenance. Interconnecting cabling must be provided to connect the WTG to the utility network through the transformer and the protective device.

4.6.3.2 APPROACH

The utility interface design follows conventional utility practices for matching the voltages of two systems through a step-up transformer. Protection of the transformer with an oil circuit recloser, which is a three phase device to preclude single phase operation of the generator, is somewhat of a departure from standard practice since the available devices are an order of magnitude larger than what is actually required for a load as small as the WTG. Components and construction of the interfacing equipment comply with NEC, NEMA, ANSI, IEEE codes and standards and utilize "off-the-shelf" components. Selection of components was based upon protection, availability and reliability so as to provide for unattended operation/protection of the WTG with a high degree of availability.

4.6.3.3 SELECTED DESIGN

The layout and installation details of the transformer, oil circuit recloser and utility connection are illustrated on NASA Dwg. No. CF758981 (W1015F76). The transformer is a General Electric Compad III, 3 phase, oil cooled, padmounted distribution transformer. Rated at 300 kVA the transformer is a dual ratio type with the primary windings switchable from a 2400 V delta

configuration to a 4160 V grounded wye configuration. The dual ratio allows the transformer a degree of flexibility since it can be connected to a utility network with a voltage level of either 2400 or 4160. The dual voltage switch is located in the high voltage compartment.

Three 3 kV lightning arresters are mounted in the high voltage compartment on each phase to provide lightning protection for the transformer. High voltage connections are live front and of radial feed configuration. A tap changer is located in the high voltage compartment which provides five voltage taps in 2-1/2 percent increments to compensate for variations in system voltage from 100 to 110 percent of rated voltage at rated kVA. Tap changing is achieved only in the de-energized condition and is set according to the conditions at the specific site. The secondary side of the transformer is rated at 480 V in a delta configuration.

The transformer is designed to provide underground service and installation on a concrete pad. The primary and secondary cables enter the transformer from below through openings in the concrete pad. All live components are completely enclosed in locked compartments for maximum safety.

The recloser is a McGraw-Edison type W recloser rated 560 amperes, 14.4 kV with an interrupting capacity of 10 kA rms symmetrical. Oil is utilized as the arc interrupting medium. Movable bridge type contacts provide two breaks in series on each of the three phases. Tripping is initiated by a series trip coil which releases the stored energy trip mechanism when an overcurrent occurs. Shunt lockout at 48 VDC is employed to remotely trip the recloser based on input from the control and relay components located in the switchgear. The reclosing feature of the device is not used such that a trip condition opens the recloser and locks it out.

Contact closing energy is provided by a closing solenoid. Shunt closing at 48 VDC is employed to remotely close the recloser based on input from the manual control switch in the switchgear.

Multi-ratio bushing type current transformers are provided as part of each bushing on the utility side of the recloser. Taps are available to provide current ratios of 600/500/400/300/200 or 100 to 5. The current transformers provide input to the recloser associated relays located in the switchgear.

The recloser is located within a McGraw-Edison transclosure housing model 76E153F1 to allow for padmounting of the recloser. The transclosure provides a tamperproof housing which conceals all live components for maximum safety. Wall mounted insulators are provided to support the incoming and outgoing high voltage cables prior to terminating them at the bushings to relieve mechanical stress at the bushings. Figure 4.6.3-1 shows the recloser and Figure 4.6.3-2 shows the transcloser housing within which the recloser is located.

As shown on NASA Dwg. No. CF758981 (W1015F76), the cable which connects the utility network to the recloser is of five kV construction installed in underground conduit. At the riser pole, where the cable is terminated, three kV

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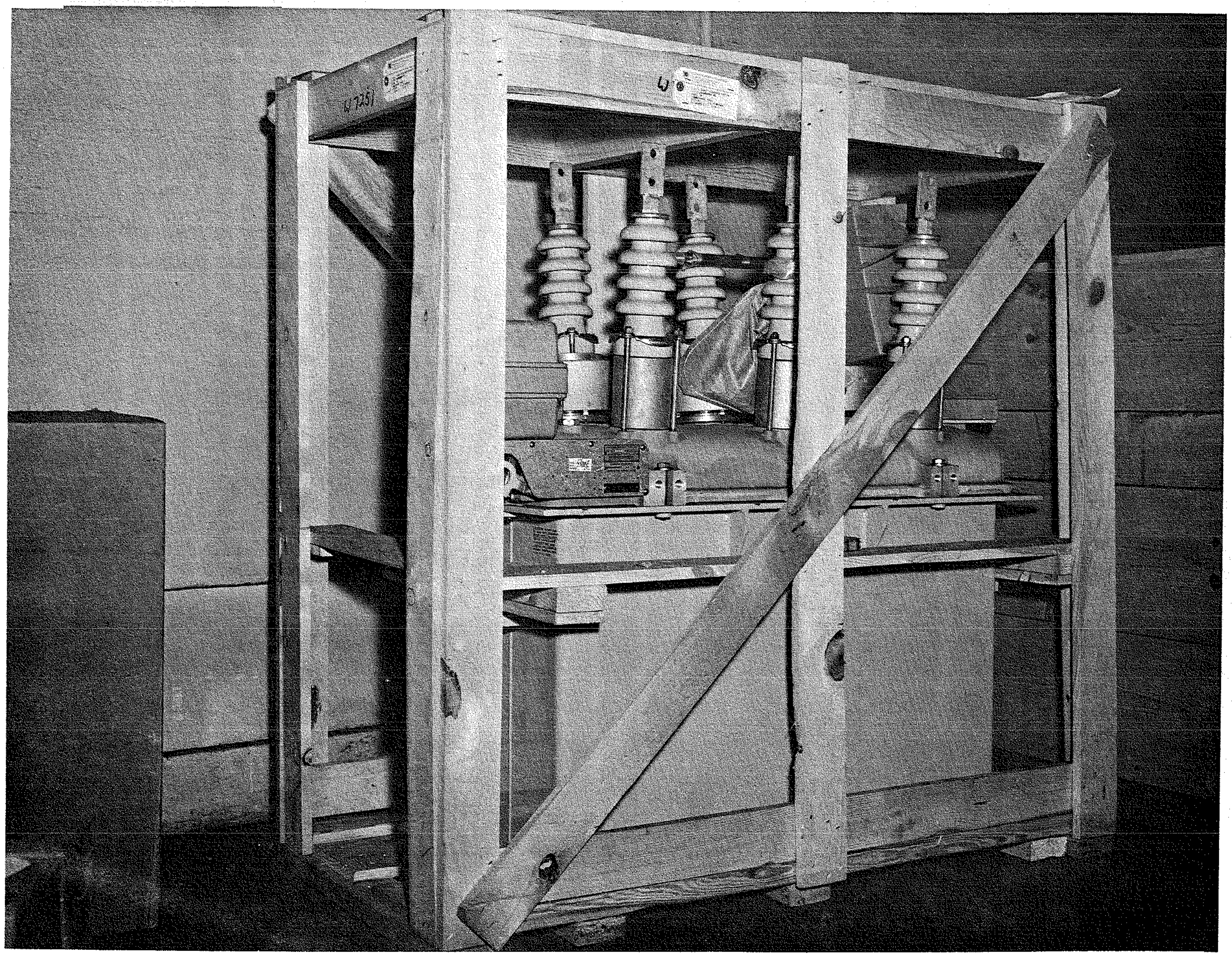

Figure 4.6.3-1. MOD-OA Oil Circuit Recloser

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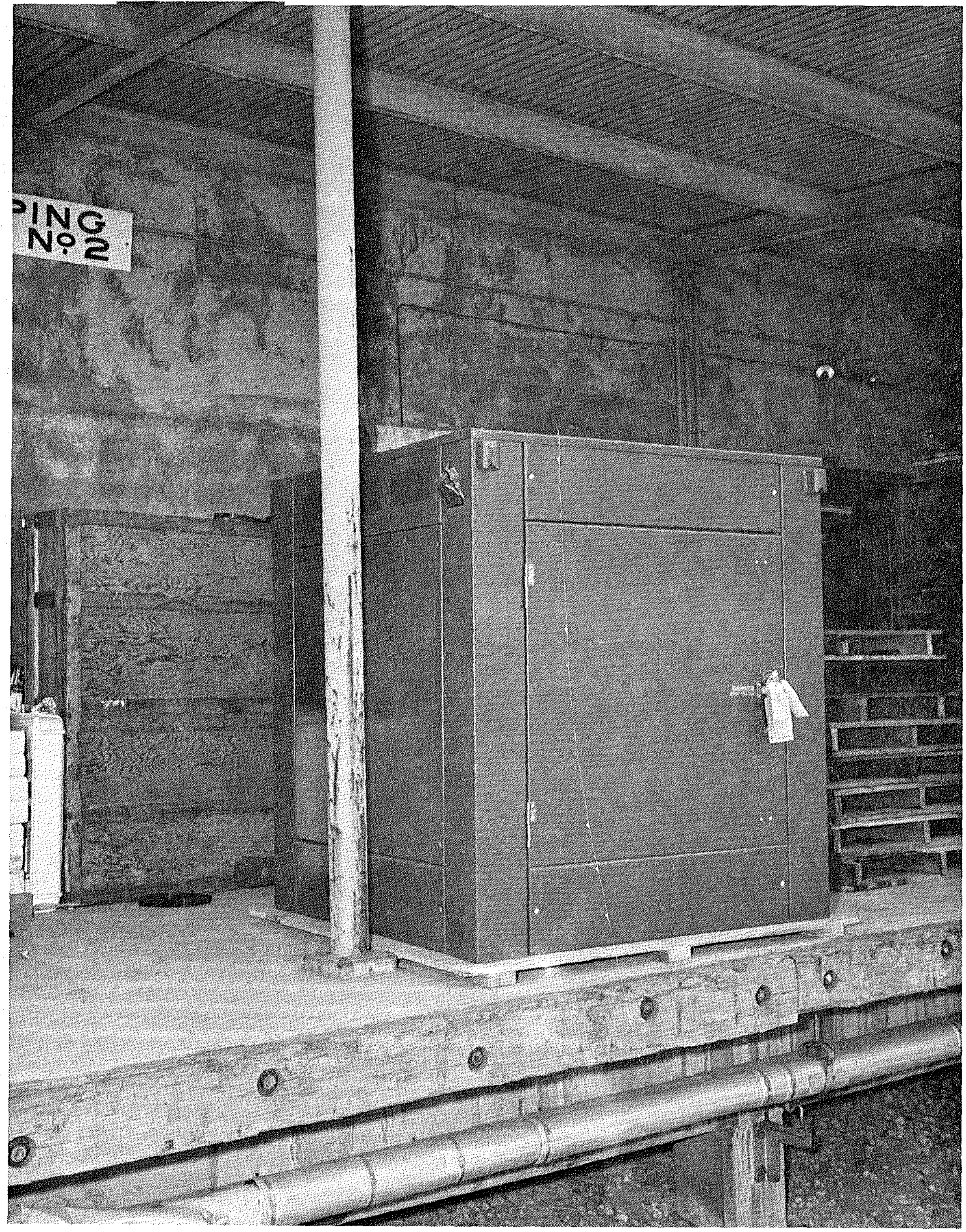

Figure 4.6.3-2. MOD-OA Transclosure Housing

lightning arrestors are installed to protect the cable and components from lightning. The cable connecting the recloser to the transformer is also of five kV construction installed in underground conduit. The low voltage cable which connects the secondary of the transformer to tie breaker CB2 is rated for 600 V and installed in underground conduit. All cables utilized for the utility interconnection are single conductor, stranded copper with insulation and jacket suitable for the environment in which they are installed.

4.6.4 SLIP RINGS

The wind turbine design includes a hub which rotates in relation to the bedplate and a bedplate which rotates in relation to the stationary tower. The WTG design must include means to transmit power, control and instrumentation across these rotating interfaces.

4.6.4.1 REQUIREMENTS

The tower device must be capable of transmitting power, control and instrumentation across the rotating bedplate. The generator output requires four contacts rated at 350 A, 480 V, 60 Hz. To accommodate the higher level ac power and control functions for devices located in and on the nacelle ten contacts rated at 50 A, 480 V, 60 Hz are required. Instrumentation, control and 120 V distribution to the auxiliary electronics package requires ninety contacts rated at 5 A, 120 V, 60 Hz. To preclude the introduction of noise the dynamic resistance of each 5 A, 120 V contact must not exceed ten milliohms.

Since the unit will be located in part below the skirt of the nacelle it must be sealed to protect the internals from the elements. A temperature range of -20 to +120°F (-28.9 to +48.9°C) is imposed on the design.

The low speed shaft device must be capable of transmitting control and instrumentation across the rotating low speed shaft to the bedplate. The interconnections associated with RMU #1, the blade angle transducer, the blade pitch servo valve and the failsafe solenoids require a total of thirty six contacts rated at five amperes, 120 V, 60 Hz. The dynamic resistance requirements for these contacts are the same as those of the tower device. A temperature range of -20 to +120°F (-28.9 to +48.9°C) is imposed on the design.

4.6.4.2 APPROACH

The method of transmitting power, control and instrumentation across the rotating interfaces followed the proven technology of slip rings which were successfully utilized in the MOD-0 design. The use of a limited cable wrap scheme for the tower device was considered as an alternative. However, due to the large number of connections and the complications of limiting yawing motion, so as not to exceed a relatively small number of cable wraps, the limited cable wrap scheme was abandoned in favor of the more conventional slip ring design.

4.6.4.3 SELECTED DESIGN

The slip ring assemblies were made to NASA Specification 3-826245 by Fabricast. Each slip ring consists of silver graphite brushes on bronze rings. Each brush is spring loaded to maintain contact pressure. All external connections are made of stud type terminals.

Assembly of the tower slip ring is detailed on NASA Dwg. Nos. CF758973 and CF758974 (W1015F74, 1015F75, and 1015F79). Wiring of the tower slip ring is illustrated on NASA Dwg. No. CF758974 (W1015F75).

Assembly of the low speed shaft (gearbox) slip ring is detailed on NASA Dwg. No. CC758972 (W1015F73). Wiring of the low speed shaft slip ring is illustrated on NASA Dwg. No. CF758983 (W1016F07). Figure 4.6.4-1 shows the low speed shaft slip ring installed in the wind turbine.

4.7 CONTROL SYSTEMS

The MOD-OA wind turbine is designed to provide for fully automated, unattended operation of the wind turbine tied to a utility network. To achieve this objective the wind turbine control system incorporates the capability to monitor wind conditions, maintain alignment with the wind, control rotor speed and power level, and startup, synchronize and stop the wind turbine in a safe manner. In addition key parameters are continuously monitored to assure that critical items are operating within specified tolerances and provisions are made to provide a remote operator with the capability to start and stop the wind turbine.

To accomplish these functions, the wind turbine incorporates five distinct control systems. The blade pitch control system adjusts blade pitch to control either rotor speed or generator power. The yaw control system provides alignment between the wind turbine and the wind. The microprocessor controls the automatic operation of the machine including startup, synchronization and shutdown. The safety system monitors system operation and initiates wind turbine shutdown when out of tolerance conditions are detected. The remote control and monitoring system provides a remote operator with the capability to start or stop the wind turbine and to monitor system performance.

Figure 4.7-1 depicts the interactions of the control system. Interfacing of the five systems is achieved through the microprocessor.

4.7.1 BLADE PITCH CONTROL

4.7.1.1 REQUIREMENTS

Blade pitch control is required to regulate both rotor speed and power. The control system must be capable of starting up the wind turbine by ramping the blade angle using position control until a five rpm rotor speed is achieved. Above a rotor speed of five rpm, speed control is required to increase the rotor speed to 40 rpm by ramping the speed setpoint. Once the 40 rpm speed is

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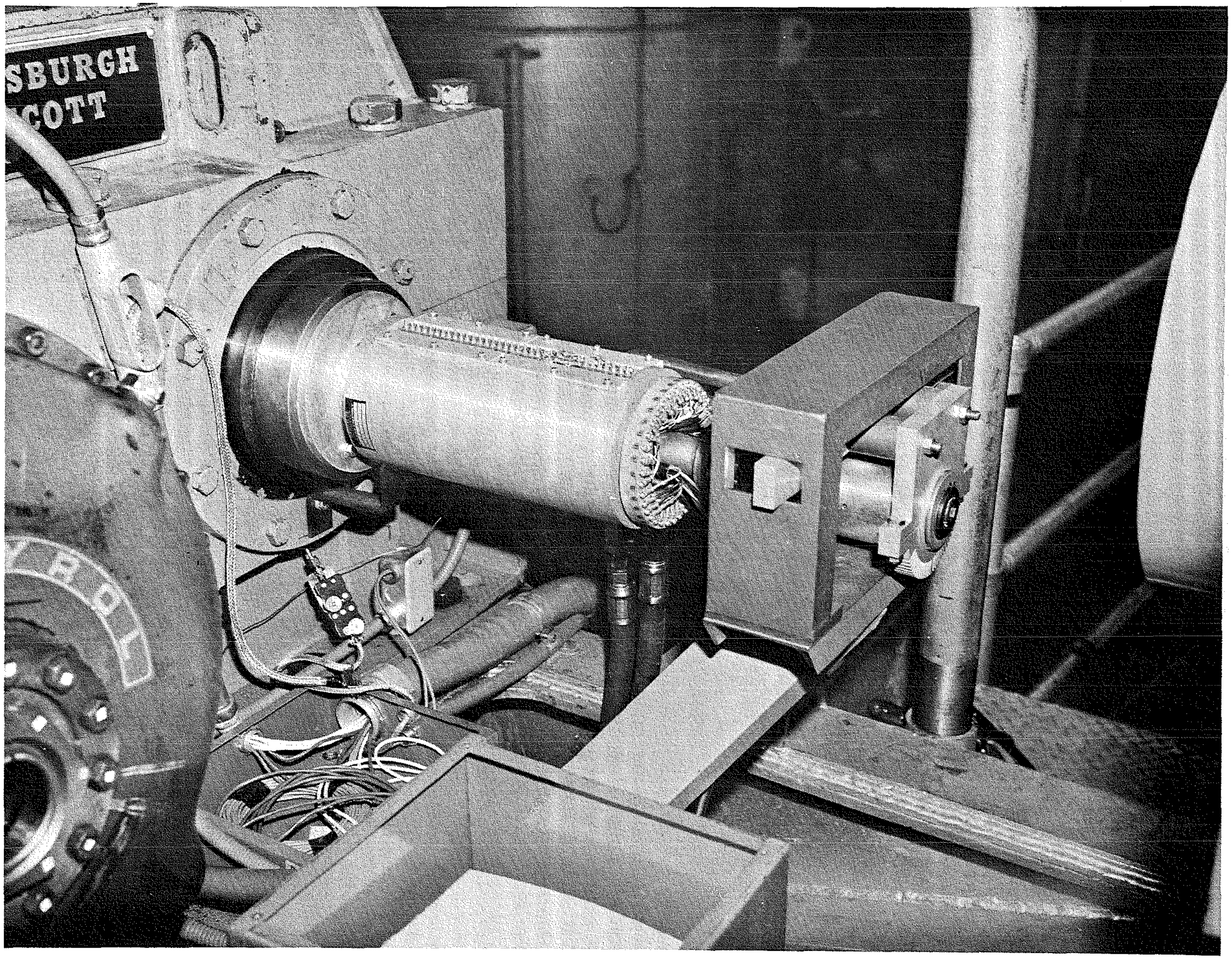

Figure 4.6.4-1. MOD-OA Rotor Slip Ring

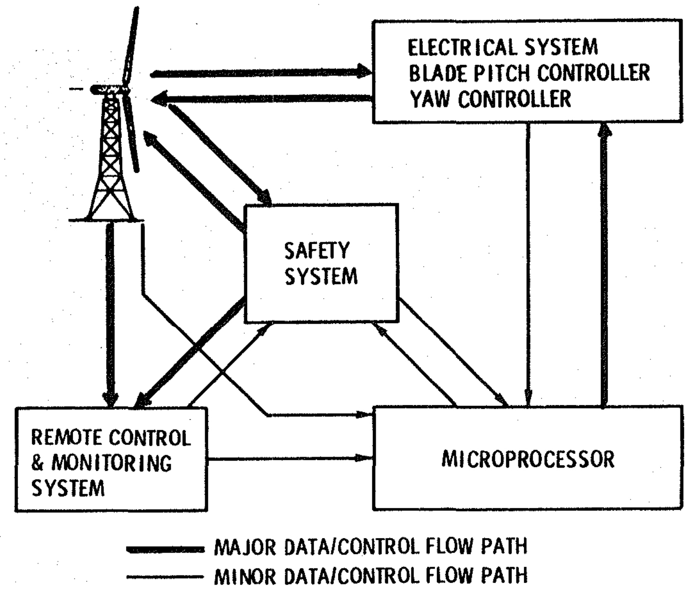

Figure 4.7-1. MOD-OA Control System Interfaces

reached and the generator is synchronized with the utility network, the blade pitch control must be capable of transferring to the power control mode with a setpoint of 200 kW.

During operation in wind speeds less than full power rating, the pitch controller should adjust the blades so as to produce maximum power from the available wind. At wind speeds in excess of full power rating, the blades must be pitched to spill the excess wind. At wind speeds greater than 40 mph (17.9 m/s) at 100 ft. (30.5 m), the blades must feather to shut down the wind turbine to avoid excessive stress on the system.

Upon a command to shutdown the blade pitch angle must be reduced until zero output power is generated and the tie breaker opened. The blade pitch must continue to decrease until the rotor reaches standstill and the blades feathered at an angle of -90°.

4.7.1.2 APPROACH

The MOD-OA blade pitch control was designed using the MOD-0 concept which had provided satisfactory performance on the MOD-0 machine. The concept of hydraulic actuation by means of a blade pitch servo utilizes standard components and performs in a reliable manner.

4.7.1.3 SELECTED DESIGN

As described in detail in Section 4.1 the blade pitch is changed hydraulically as activated by a closed loop servo system. The servo controller operates in three distinct modes: direct control of pitch angle, closed loop pitch control

to regulate speed and closed loop generator power control supplemented by wind speed compensation. The power control mode is utilized for normal operation of the wind turbine once it is synchronized with the utility network. Speed control is normally used during start up or unsynchronized operation. Since the speed control loop is not effective below five rpm direct pitch control is utilized to accelerate the wind turbine from a dead stop to the point where speed control can be utilized. Direct pitch control is also used to feather the blades during shutdown.

Rotor speed is a slightly nonlinear function of blade pitch and wind speed, and is controlled with a proportional plus integral control function sensing rotor speed. The integral control provides accurate long term regulation required for frequency stability in the speed control mode. Variations in wind speed result in rotor speed variations which are beneficial in synchronizing.

The normal control function is the power control mode in which pitch is controlled to limit the power output to the nominal 200 kW rating of the machine. Under wind conditions below those required for full power operation, pitch is controlled to produce maximum power from the available wind. Since wind speeds less than ten mph (4.5 m/s) at hub height are not sufficient to produce power the machine is usually shut down when this condition exists.

In the power control mode, both power and wind speed are sensed to control the blade pitch. Closed loop power control is provided through an integral control loop sensing generator output power. Wind speed is utilized in a feed-forward or anticipating mode as a means of attenuating the effect of wind speed changes. Greater stability and accuracy are obtained with the feed-forward loop, particularly in the presence of high speed gusty winds. Wind speed is sensed by a nacelle mounted anemometer.

To limit blade stress the pitch rate is limited to eight degrees per second by hydraulic orifices. The controller limits the maximum pitch angles for feather and maximum power. The controller, based on input from the microprocessor, can vary the maximum power angle as a function of wind speed. In addition controller gain can be programmed as a function of wind speed. Figure 4.7.1-1 is a block diagram of the blade pitch control scheme in the power control mode with wind feed forward.

The controller selected for the MOD-OA pitch control system is a BAFCO, Inc. Model 846 controller. The controller is located on the control rack situated in the control building. This unit is identical to the controller utilized for the MOD-0 machine. Layout of the controller is detailed on Drawing W1016F15 Electrical Connection Diagram Pitch Controller. A two position switch is provided to select the readout of a panel meter which displays either "error" or "output". A three position mode switch is provided to select whether the controller is in the "manual" or "automatic" mode or whether the mode is to be controlled "externally" in power control. Bumpless transfer is provided between the automatic and manual modes.

A two position switch is utilized to select the readout of a panel meter which displays either the output of the servoamplifier or inner loop feedback/ position. Three separate components are provided on the panel to adjust controller setpoints for the manual, speed and power control modes.

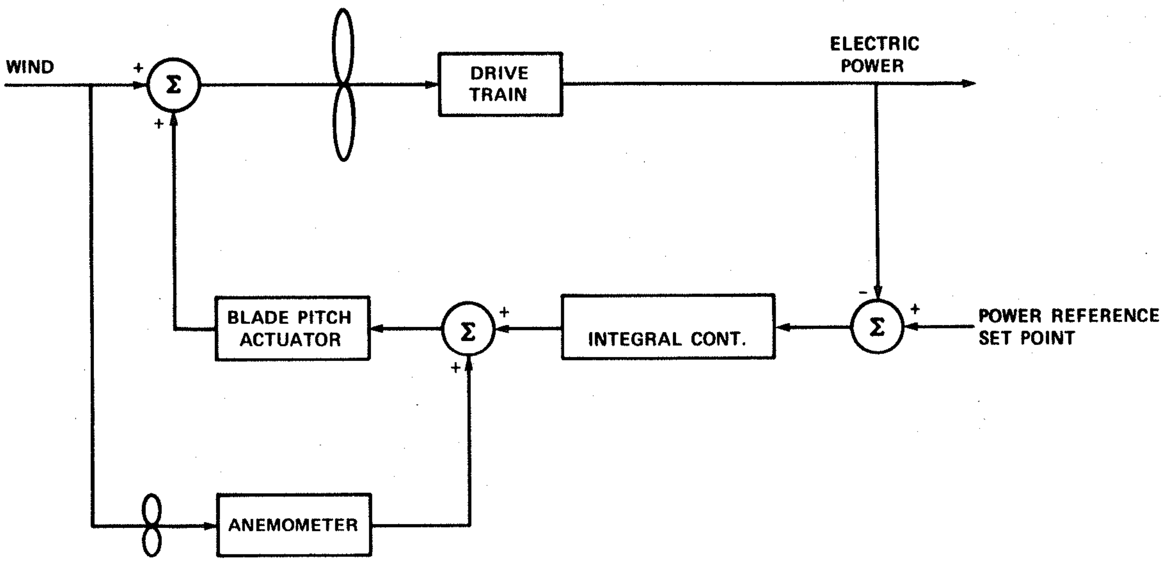

Figure 4.7.1-1. Block Diagram of Blade Pitch Control in the Power Control Mode with Wind Feed Forward

4.7.1.4 SUPPORTING ANALYTICAL RESULTS

A dynamic analysis of the active pitch control used on the MOD-0 machine was performed.[50]

4.7.2 YAW CONTROL

4.7.2.1 REQUIREMENTS

Yaw control is required to maintain alignment between the wind turbine and the wind so as to maximize wind capture. The rate of yawing is limited by the stresses induced by the gyroscopic effects of blade rotation to one degree per second. The control system associated with yawing must provide for sensing the position of the nacelle relative to the wind and initiating corrective action to align the nacelle with the wind whenever the yaw error exceeds a specified set point.

Since the wind turbine is inoperative when wind speed is less than ten mph (4.5 m/s) at hub height, the control scheme must be capable of inhibiting yaw motion when such low wind conditions exist. When the yaw error becomes excessively large due to system inability to maintain alignment with the wind the control system must initiate a safety shutdown of the wind turbine. The control system must have provisions for both manual and automatic control to allow for manual yawing during maintenance and checkout periods.

The mechanical components which constitute the yaw drive system, as discussed in Section 4.4, include three fixed brakes which are applied when yawing is not

required and partially released during yawing maneuvers. The yaw control system must properly control the hydraulic system associated with the fixed brakes to satisfy these requirements.

4.7.2.2 APPROACH

The MOD-OA yaw control system is an outgrowth of the MOD-0 yaw control system which provided reasonable control of yaw motion. The control system utilizes standard relay logic to satisfy the requirements of the system.

4.7.2.3 SELECTED DESIGN

Details of the yaw control system are illustrated on NASA Dwg. Nos. CF759028 and CF759044 (W1016F13 and W1016F23). The yaw controller senses directional error from an anemometer/wind vane mounted on the nacelle. The wind vane monitors yaw error by measuring the apparent wind direction relative to the nacelle. As shown in the yaw system block diagram of Figure 4.7.2-1, the yaw error signal is filtered by a ten second time constant filter to eliminate noise and response to transient wind shifts. The 25° deadband of the controller must be exceeded for several seconds prior to initiation of corrective action. Once the controller determines yawing is required the fixed brakes are released. Both yaw drive motors are started simultaneously in the appropriate direction once the fixed brake pressure is reduced to 150 psig ($1.03 \times 10^6 N/m^2$). Yawing continues until the filtered error is less than 7-1/2° at which time the drive motors are deenergized. The motors are allowed

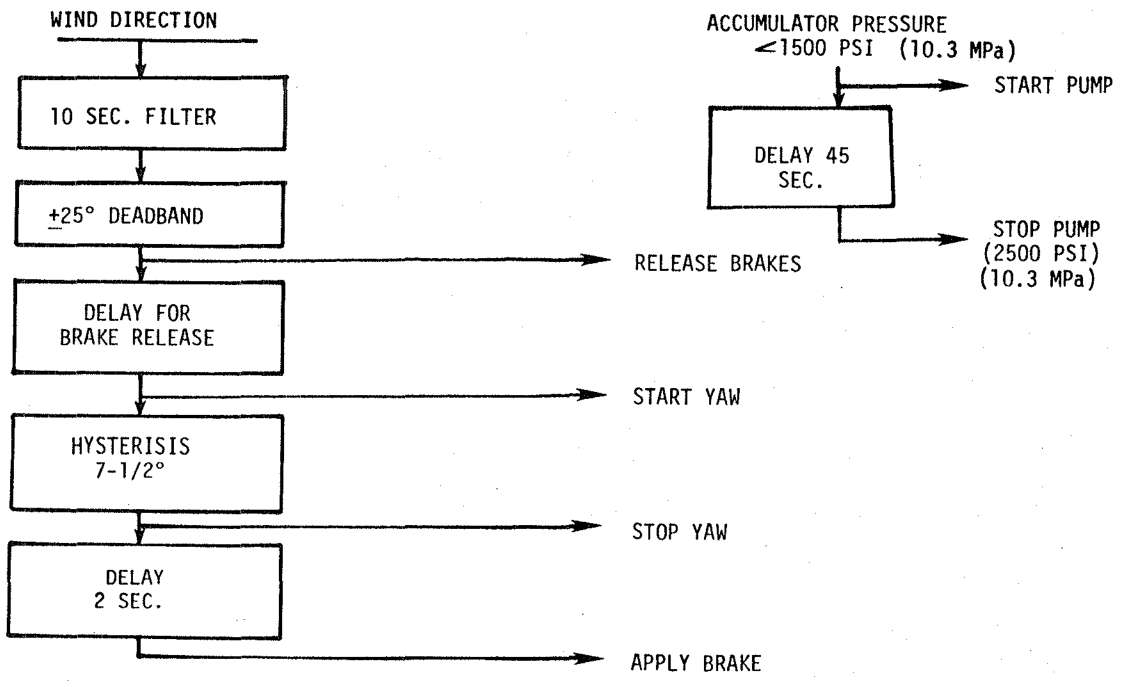

Figure 4.7.2-1. MOD-OA Yaw Control Block Diagram

to coast to a stop for approximately two seconds at which time the fixed brakes are reapplied. The net effect is that the nacelle is driven to within a few degrees of zero for each correction. Greater control accuracy resulting from a narrower deadband would increase wind capture however, the increased accuracy would require more yaw maneuvering. Prior to decreasing the deadband, fatigue on the yaw system and power consumption must be evaluated relative to the potential for increased wind capture.

Since the wind turbine does not produce power when the wind speed is less than eight mph (3.6 m/s), the yaw drive system is disabled when such a wind condition exists. To eliminate excessive switching of the control circuit the windspeed signal is filtered by a one minute time constant filter and a one mph hysteresis is factored into the design.

As illustrated on NASA Dwg. No. CF759047 (1016F25), a yaw control panel is provided on the control rack in the control building. The operator may select auto, off and manual modes of operation. In the manual mode either the clockwise or counter-clockwise direction can be selected. Both wind direction and nacelle direction are displayed by digital panel meters on the control panel.

An accumulator supplies 1500 to 2500 psig (10.3 to 17.2 MPa) to the fixed brakes when no yawing is required. When the yaw controller initiates a yaw correction, the brake pressure is decreased to an adjustable range of 0 to 100 psig (0 to 0.69 MPa). The decreased pressure on the brakes provides a damping drag force during yawing. A hydraulic pump recharges the accumulator when its pressure drops below 1500 psig (10.3 MPa). Overpressurization of the accumulator is limited by parallel relief valves located between the pump discharge and the hydraulic reservoir. The pump is prevented from operating if the fluid level in the hydraulic reservoir is insufficient. A hydraulic schematic of the yaw brake system is illustrated on NASA Dwg. No. CF759019 and CF760485 (W1015F80).

The yaw control system interfaces with the safety system in four distinct areas. Hydraulic fluid level and accumulator pressure are monitored and initiate a safety shutdown on low fluid level or low accumulator pressure. Yaw error in either the clockwise or counterclockwise direction in excess of 40 degree for a ten second duration initates a safety shutdown. In winds less than eight mph (3.6 m/s) when the yaw drive system is inoperative this shutdown mode is defeated. During startup of the wind turbine the yaw error shutdown is disabled for a period of two and a half minutes to allow the nacelle to align with the wind. An instantaneous shutdown is provided if the yaw error exceeds seventy degrees.

4.7.2.4 SUPPORTING ANALYTICAL RESULTS

Figure 4.7.2-2 shows the pointing accuracy of the nacelle for tests run with the MOD-OA yaw controller tested in the MOD-0 machine. The figure plots the percentage of time during which the yaw error was within the various five degree wide error bands. For this particular test the nacelle was within five degrees of zero 29 percent of the time and within ten degrees 55 percent of the time. Errors indicated in the ninety degree error region occurred while the machine was not operational.

Pointing accuracy can be converted to wind capture by the cosine of the nacelle error. For this particular test the wind capture is 94 percent. Wind capture is not important above rated wind speed since the blade pitch angle is automatically adjusted to control power, thereby correcting for the loss of wind. Below rated wind speed the 94 percent wind capture represents a six percent loss of output power.

The data plotted in Figure 4.7.2-2 was collected during a one and a half hour period with winds ranging from 10 to 25 mph (4.5 to 11.2 m/s). During this period, the wind turbine was yawing 7.5 percent of the time. The test results indicate very good pointing accuracy with a peak deviation from the average only a few degrees.

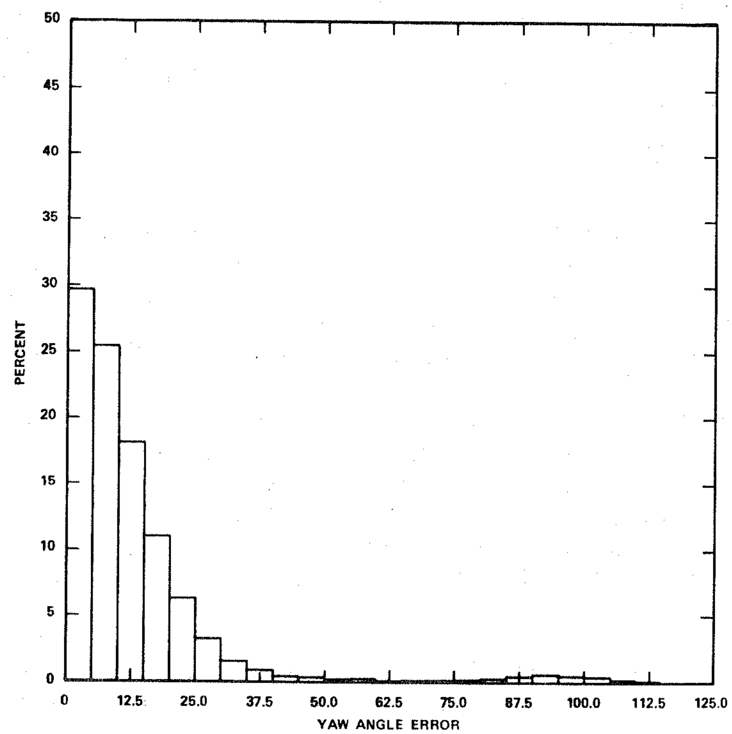

Figure 4.7.2-2. Yaw Angle Error

4.7.3 GENERATOR CONTROL

4.7.3.1 REQUIREMENTS

Since the MOD-OA design incorporates a synchronous generator provisions are included in the control scheme to regulate the excitation of the generator field. The voltage regulator is capable of operating in both the manual and automatic modes. In the manual mode field excitation is adjustable from zero to rated value. In the automatic mode the regulator senses generator voltage to within two percent of rated value from no load to full load at 0.8 power factor. The regulator also includes provisions to sense reactive power and provide compensation for power factors below rated value when the generator is paralleled with other generators.

As part of the MOD-OA generator control scheme the phase angle and frequency of both the generator output and the utility network are monitored and the blade pitch adjusted to speed the generator up or slow it down as required. When the generator phase angle is within a preselected breaker closing angle bandwith for a given time interval the synchronizing device provides contact closure to close tie breaker CB2 which parallels the generator with the utility network.

4.7.3.2 APPROACH

The generator control scheme was developed through the use of standard electric utility methods of controlling synchronous generators. In the case of a wind turbine, the governor associated with the generator is the pitch of the blades which control the input speed to the generator. The control scheme for MOD-OA duplicates that which was successfully utilized on the MOD-0 machine. Components selected for control of the generator are standard, off-the-shelf components utilizing proven technology to provide reliable and cost effective generator control.

4.7.3.3 SELECTED DESIGN

The design selected to control generator output is shown in elementary form in Figure 4.7.3-1. The voltage regulator for the MOD-OA electrical system is a Basler Electric Model SR4A static voltage regulator. When used in conjunction with a Basler Electric MVC104 manual voltage control module the regulating system provides for manual and automatic modes of operation.

In the automatic mode the regulator senses the output voltage of all three phases of the generator and provides voltage regulation as required. The regulator maintains output voltage within two percent of rated value from no load to full load at 0.8 power factor. Incorporated in the voltage regulator are provisions for reactive power sense to provide compensation for power factors below rated value when the generator is paralleled with other generators.

In the manual mode the automatic voltage regulator is removed from the line and the generator voltage is manually controlled by an autotransformer in the manual control module. The field excitation of the generator is manually adjustable from zero to rated voltage.

As shown in Figure 4.7.3-1 a VAR controller is used in conjunction with the voltage regulator to control reactive load current. The device selected for this application is a Basler Electric Model SCP250 VAR/power factor controller. The SCP250 senses single phase generator output voltage and current. Based upon these inputs the controller provides an output signal that is electronically injected in series with the voltage regulator voltage adjusting rheostat. As a result, the voltage regulator adjusts its output until the selected reactive load current is attained. A "b" contact from tie breaker CB2 is interlocked with the VAR controller such that the controller is disabled when the tie breaker is open. The generator is normally operated with the VAR controller set at approximately 90 KVAR leading. In this mode of operation, the possibility of synchronous pullout due to transient loading, such as a gust of wind, is minimized.

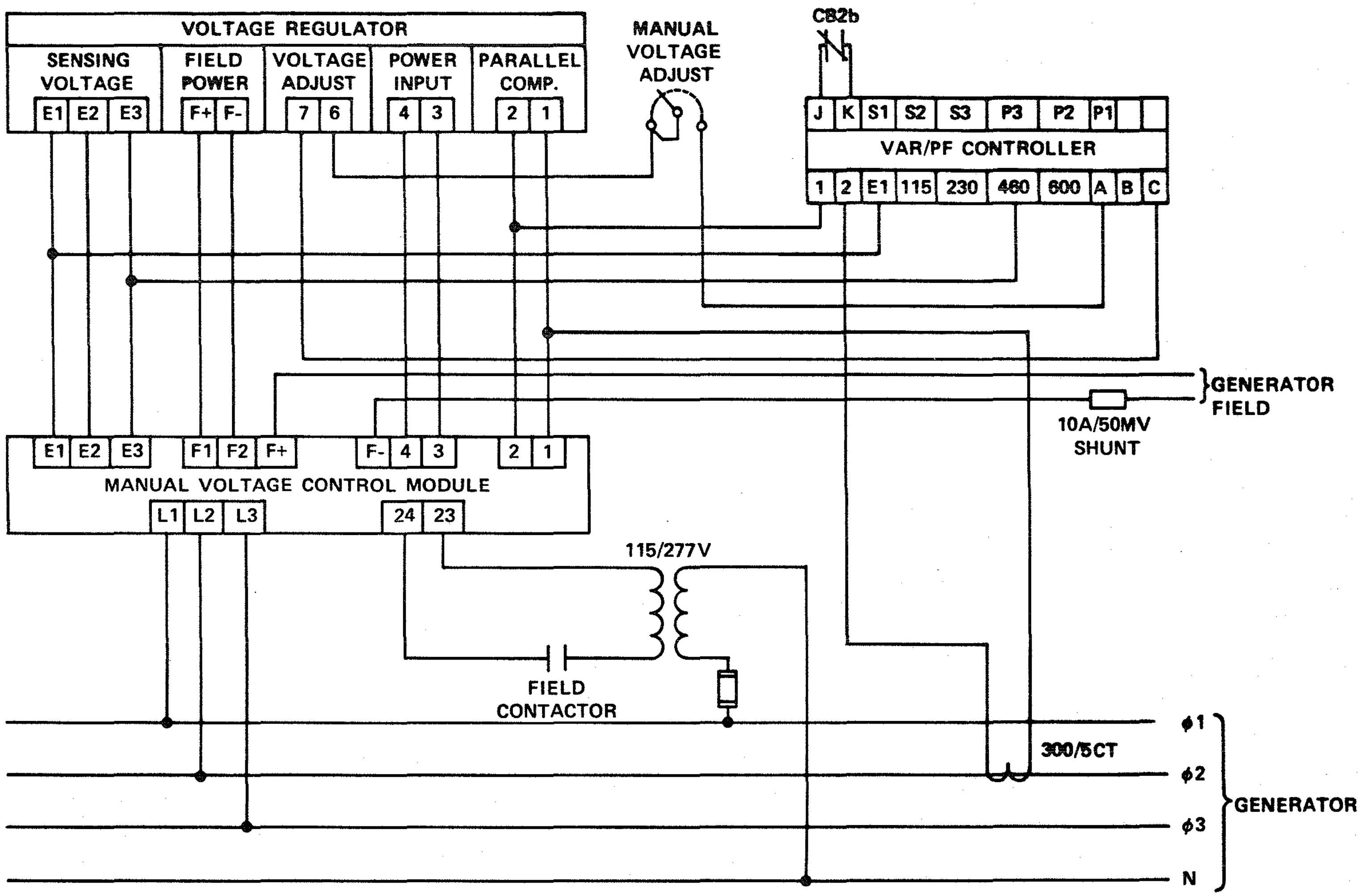

Figure 4.7.3-1. Generator Control Elementary

Input power to the voltage control scheme is provided by a 277/115 V stepdown transformer. A field contactor, which can be closed manually from the manual control panel or automatically from the microprocessor, is located in the input power circuit to enable/disable the control scheme as required. The dc output from the manual voltage control module is wired to the field winding of the generator with a 10 A, 50 mV shunt installed in series with the field circuit. The shunt provides an input to remote multiplexer unit number 3 for monitoring of the field current.

The synchronizing device selected for the MOD-OA design is a Basler Electric Model PRS370 auto-synchronizer. The auto-synchronizer monitors, on a single phase basis, the phase angle and frequency of the generator output and the utility network. It senses the difference between the two systems and provides a corrective signal to the blade pitch control mechanism to speed up or slow down the rotor as required. When the generator phase angle is within the preselected breaker closing angle bandwidth for 0.75 seconds, the synchronizer provides a closing signal to tie breaker CB2 to parallel the systems. Simultaneously with the breaker closing the signal to the blade pitch controller is automatically reset to zero. The synchronizer has provisions for selecting breaker closing angles of ± 5°, ± 10°, ± 15°, and ± 20° by installation of jumpers on the device.

Details of the installation and connection of the generator control equipment are provided on NASA Drawings CF758971 (W1016F02) and CF759035 (W1016F20). Details of the interface between the auto-synchronizer and tie breaker CB2 and the VAR/power factor controller and tie breaker CB2 are illustrated on NASA Dwg. CF760495 (W1016F32).

4.7.4 SAFETY SYSTEM

4.7.4.1 REQUIREMENTS

The concept of unattended operation of a wind turbine requires that a protective system monitor the wind turbine and safely shutdown the machine when a malfunction is detected. Wherever possible the design of such a system should be redundant and fail safe. The safety system must be capable of operating independently of all other control systems and be sufficiently reliable so as to prevent unrequired or spurious shutdowns.

4.7.4.2 APPROACH

The safety system is designed on the concept that an emergency shutdown of the wind turbine should be effected when any one of several key operational parameters exceeds its safe limit. To protect against a malfunction of the emergency shutdown system a set of redundant sensors is provided which act independently of the emergency sensors to effect a safe shutdown. Additionally, since rotor overspeed is a malfunction with potentially catastrophic results, a critical shutdown of the system is included in the design when rotor speed reaches 45 rpm. The safety system is designed such that component failures within the system result in a system shutdown.

4.7.4.3 SELECTED DESIGN

The safety system developed for the MOD-OA wind turbine is shown in block diagram form in Figure 4.7.4-1. A series of primary sensors is connected to an interface/annunciator circuit. The annunciator, in the control building, is utilized to permit a rapid determination of the cause of a system shutdown. A condensed version of the annunciator function is transmitted to the remote control and monitoring station to provide the remote operator with an indication of the nature of a shutdown prior to dispatching operating personnel to the wind turbine site. The output of the interface circuitry controls a relay logic system which is integrated with the wind turbine electrical system to effect the shutdown.

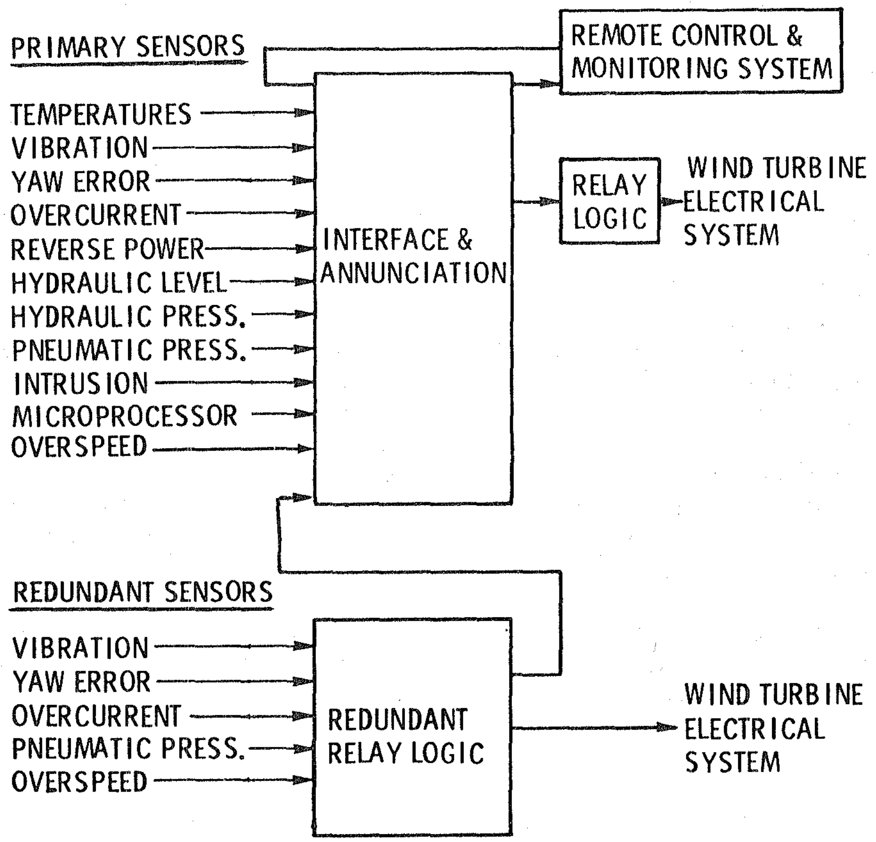

Figure 4.7.4-1. Safety System Block Diagram

A second set of sensors provide partial redundancy of the error detection/shutdown system. Initiation of a shutdown in the redundant mode is accomplished by independent sensors, located in the nacelle, by switching nacelle wiring. In the redundant system signals are not run from the nacelle to the control room and back to the nacelle to effect a shutdown.

The primary shutdown sensors consist of those sensors identified as follows:

Front low speed shaft bearing temperature	BT1
Rear low speed shaft bearing temperature	BT2
Front high speed shaft bearing temperature	BT3

Gearbox oil temperature	GOT
Alternator winding temperature	AWT
Pitch hydraulic fluid temperature	HOT
Pitch hydraulic pump motor temperature	HMT
Rear low speed shaft bearing vibration	VSIB
Emergency feather bottle pressure	$PSIA_b$
Rotor brake bottle pressure	$PS2A_bI/PS2B$
Pitch hydraulic pressure	$PS1^B$
Yaw brake accumulator pressure	LP107
Pitch hydraulic reservoir level	LS1
Yaw hydraulic reservoir level	LP100
Yaw error	08D356
Intrusion Alarm	IA
Phase - A overcurrent	OCVR1
Phase - B overcurrent	OCVR2
Neutral overcurrent	5IN
Reverse power	RPR1
Rotor speed	07R302 (42 rpm)
Microprocessor	Cycle timer

The operation of any of these sensors will cause an emergency shutdown. Once an emergency shutdown is initiated, the emergency feather valves are opened and the blades move toward the feather position at a rate of four degrees per second. In addition, the pitch hydraulic pump is turned off such that the emergency feather bottle will feather the blades even if the emergency feather solenoid valves should fail to operate. After a three second time delay, both the generator field contactor and the synchronizing contactor are opened. A delay of three seconds is provided to prevent overspeeding when the load is dropped from the generator. A halt command is sent to the microprocessor which instructs the microprocessor to stop. If the shutdown is initiated by the yaw hydraulic level sensor, the hydraulic pump motor will also be shut down as part of the shutdown sequence.

In the event that the rotor speed reaches 45 rpm, overspeed switch OSS2 will initiate a critical shutdown (an emergency shutdown and an engagement of the rotor brake). This shutdown path is provided in redundancy to the normal overspeed shutdown which should be effected by overspeed switch OSS1 at a rotor speed of 45 rpm.

The faults associated with an emergency shutdown will be indicated at the safety system annunciator and at the remote control and monitoring panel. Once an emergency shutdown has been effected the system must be manually reset at the wind turbine site prior to resuming operations.

The redundant shutdown system is intended as a backup to ensure a safe system shutdown in the event of a failure in the primary shutdown system. The sensors associated with the redundant system are not as numerous, however, in general it duplicates the primary shutdown system. The redundant shutdown system utilizes sensors and wiring which are separate from the primary shutdown system. The redundant shutdown sensors consist of those sensors identified as follows:

Front low speed shaft bearing vibration
Yaw error

Phase C overcurrent	OCVR3
Emergency feather bottle pressure	PS1A
Rotor brake supply pressure	PS2A
Overspeed	OSS1

Shutdowns initiated by yaw error or overcurrent are identical to the primary system shutdown with the exception that the microprocessor gets a stop command instead of halt command. Actuation of the redundant system vibration or pneumatic pressure sensors result in an emergency feather only while actuation of the overspeed sensor results in an emergency feather and application of the rotor brake. A redundant shutdown initiated by vibration or pressure will result in emergency blade feathering. As a result of the emergency feather a complete emergency shutdown will be effected since the reverse power or overcurrent sensors will desynchronize the machine and turn off the hydraulic pump through K4 relay.

Elementary diagrams of the safety system are illustrated on NASA Dwgs. No. CF759026 and CF759027 (W1016F11 and 1016F12). Location of the sensors associated with the safety system is shown on NASA Dwg. No. CR758975 and CR758976 (W1015F43). Location of the safety shutdown panel in the control rack is shown on NASA Dwg. No. CF759034 (W1016F19). Electrical connections at the safety shutdown panel are illustrated on NASA Dwg. No. CF759043 (W1016F22) as well as the indicating lights and the reset pushbuttons associated with the safety shutdown panel.

4.7.5 MANUAL CONTROL

4.7.5.1 REQUIREMENTS

The MOD-OA wind turbine control system must provide for manual operation of the wind turbine for checkout testing. The manual control scheme must be designed such that the safety shutdown system remains operational during manual control operations. Provisions must be incorporated in the design to select control modes between manual, auto and off. Manual control must be provided to operate the oil circuit recloser, tie breaker CB2, the yaw drive system, the blade pitch controller, the hydraulic pump motor, the fail safe solenoids and the generator field contractor.

4.7.5.2 APPROACH

The manual control system was designed utilizing standard, commercially available switches, pushbuttons, lights and relay logic to accommodate the required manual control functions within the framework of the safety shutdown system.

4.7.5.3 SELECTED DESIGN

The majority of the manual control features of the MOD-OA wind turbine are located on the manual control panel, located on the control rack, as identified on NASA Dwg. No. CF759034 (W1016F19). The interfaces between the manual control functions and the safety shutdown system are illustrated on NASA Dwg. No. CF759027 (W1016F12). A selector switch is provided to select automatic, off and manual modes of wind turbine operation. When the manual mode is selected several functions associated with the wind turbine can be manually controlled. The hydraulic pump motor can be manually started or stopped by

operating pushbuttons on the manual control panel. An indicating light is provided which is energized when the pump is running. The fail safe solenoids associated with the blades can be released or the blades can be feathered by operating pushbuttons on the manual control panel. An indicating light is provided which is energized when the solenoids are released. The generator field contactor can be opened or closed at the manual control panel. An indicating light is provided which is energized when the field contactor is closed. Tie breaker CB2 can be closed from the manual control panel provided the synchronizing switch (43 device) is closed or the auto-synchronizer is satisfied. The tie breaker can also be opened from the manual control panel. Indicating lights are provided to indicate both the open and close positions of the tie breaker.

The pitch controller, as shown on NASA Dwg. No. CF759030 (W1016F15), includes provisions for selecting a manual operating mode. The blade pitch can therefore be manually adjusted at the pitch controller panel located on the control rack.

The yaw drive system can be selected for automatic, off and manual operating modes at the yaw control panel. As shown on NASA Dwg. No. CF759047 (W1016F25), the yaw control panel includes a selector switch which allows the operator to yaw the wind turbine in the clockwise and counterclockwise directions. Digital panel meters are provided to indicate both wind direction and nacelle direction for operator convenience.

As shown on NASA Dwg. No. CF760495 (W1016F32), the oil circuit recloser can be closed manually provided tie breaker CB2 is open during the operation. The recloser can also be tripped manually by utilizing the same pistol grip control switch located on the switchgear.

4.7.6 AUTOMATIC CONTROL

4.7.6.1 REQUIREMENTS

The MOD-OA wind turbine control system must provide for unattended operation since installations will typically be located some distance from the central power station and the expense associated with having a specially trained operator at each site is prohibitive. The automatic control system must automatically initiate startup, control normal operation and shutdown the wind turbine based upon the wind conditions. This control scheme must interface with the blade pitch control system so as to provide mode and setpoint commands to the blade pitch control system. Once the control system has been activated by an operator, no other action on the operator's part should be required unless he wants to shut down the wind turbine and/or disable the control system.

The automatic control system for the wind turbine must be flexible enough to allow for changes in control strategies associated with the wind turbine. Since numerous control strategies may be utilized, it is imperative that the selected control system have the capability to accept changes without requiring extensive time consuming modifications.

4.7.6.2 APPROACH

The automatic control system was designed utilizing standard, commercial available control components having a high degree of reliability. The concept of employing hard wired circuitry to develop the control system was discarded very early in the decision making process since every operating mode would have required different equipment and every control strategy change would have required circuit modifications, system rewiring and retesting.

Due to advances in small computer technology, which provide for significant flexibility in developing operating strategy for a wind turbine at a reasonable cost, a microprocessor was selected as the basis for the automatic control system. Additionally microprocessors were found to be extremely reliable and consistent. Once a program change is made and its performance tested, a microprocessor can be depended upon to perform in exactly the same manner repeatedly.

4.7.6.3 SELECTED DESIGN

The microprocessor selected as the heart of the automatic control system consists of an Intel 8080 central processing unit with the following equipment.

a. Sixteen A/D converters, twelve bits, with at ten volt dc input for sensing blade rpm, wind velocity (nacelle), controller tracking signal, power output, wind velocity (meteorological tower) and spares.

b. Twelve discrete 120 V, 60 Hz inputs from hydraulic pressure, rpm error, field contractor, tie breaker, recloser, supervisory control inputs and spares.

c. Eight discrete 120 V, 60 Hz, two ampere outputs for operating the hydraulic pump unit, fail-safe solenoid valves, field contactor, synchronizer and spares.

d. Eight normally open relay outputs for controller mode control.

e. Six D/A converters, ± 10 volts, for position command, rpm setpoint, load setpoint and spares.

f. Two digit display to indicate a status code which is used to display the last interrupt or the cause of the last shutdown.

g. Eight interrupts for start/stop program control.

h. 256 bytes of RAM.

i. 2K bytes of EPROM.

The microprocessor and associated equipment are mounted in the control rack in the control building as shown on NASA Dwg. No. CF759034 (W1016F19). A

microprocessor block diagram is illustrated on NASA Dwg. No. CF759031 (W1016F16) and a microprocessor flow diagram is shown on NASA Dwg. No. CF759029 (W1016F14).

The startup sequence begins by checking wind velocity. If the velocity of the wind is not between 12 and 40 mph (5.4 and 17.9 m/s), startup will not be initiated and the microprocessor continues to monitor wind velocity until it is within the acceptable range. When the wind is acceptable, the hydraulic system associated with the blade pitch system is started and the program waits for the hydraulic pressure to build up. Once the pressure is sufficient the valves holding the blades feathered are switched to allow pitching of the blades and the rotor brake is released. The blade pitch angle is slowly increased until the rotor speed exceeds five rpm. At this point the pitch controller is switched to the speed control mode and the speed setpoint increased until the synchronous speed setpoint is reached. Just prior to reaching synchronous speed the alternator field is energized. At synchronous speed the auto-synchronizer will tie the wind turbine to the utility network. The alternator field is controlled by a VAR controller and the pitch controller is switched to the power control mode with a setpoint of 200 KW. At this point the startup sequence is complete and the wind turbine is supplying power to the utility network.

Shutdown is also automatic and can be initiated by the operator, wind conditions or several checkpoints in the processor program. Upon receipt of a stop command, the pitch controller is transferred to the pitch control mode. The pitch command setpoint is equal to the pitch at which the machine had been operating. The pitch angle is then reduced at the rate of one degree per second until the power output decreases below a predetermined power level. The wind turbine is then disconnected from the utility network by opening the tie breaker and the alternator field is deenergized. Once the blades reach the fully feathered position, the pitch hydraulic system is turned off and the blade feathering valves opened.

In instances where the shutdown is initiated by unacceptable wind speed the system will automatically restart when the wind is acceptable. Startup requires a wind speed in excess of 12 mph (5.4 m/s) (hub height) and shutdown is initiated in winds less than eight mph (3.6 m/s) (hub height). The hysteresis reduces startup/shutdown cycles under light variable wind conditions. The wind speed is filtered with a one minute time constant filter to reduce cycling.

When the operator commands a shutdown, restart is automatic when he commands it, provided the wind velocity is acceptable. If a shutdown is initiated by an abnormality detected by the microprocessor the system can only be restarted after a reset at the wind turbine site.

The microprocessor tests for two faults during startup: loss of hydraulic pressure and loss of synchronization. During startup blade pitch is increased until five rpm is reached. The microprocessor considers a fault condition to exist if this speed is not reached by the time the blades are pitched at 20°.

In addition, if the wind turbine does not synchronize within fifty seconds after reaching synchronous speed, a shutdown will be initiated. Loss of synchronzation is detected by a speed error or the opening of the synchronizing contactor.

Any of these conditions, except wind speed or operator command, execute an emergency shutdown. The shutdown sequence is the same as a normal shutdown except that the emergency feather valves are opened and the microprocessor will not restart without being reset at the wind turbine site. The emergency feather rate for the blades is four degrees per second which is the fastest acceptable rate for blade loads.

4.7.6.4 SUPPORTING ANALYTICAL RESULTS

Since the microprocessor for the MOD-0A machines is identical to the one used for the MOD-0 machine, it is appropriate to discuss the initial checkout testing on the MOD-0 processor. Early program debugging was performed with the microprocessor connected to an I/O simulator. The simulator had the capability of exercising every portion of the program. Once the microprocessor was installed at the MOD-0 site the simulator was particularly useful for testing those conditions which are normally uncontrollable. For example low or high wind conditions could be simulated and the wind turbine forced to shut down even under favorable wind conditions. Utilizing such a technique all the wind turbine functions could be tested. The simulator proved invaluable in placing the MOD-0 machine in operation and made the development of MOD-0A control systems straight-forward.

The program listing for the MOD-0A microprocessor for the Clayton, New Mexico machine is illustrated in Appendix C.

4.7.7 REMOTE CONTROL AND MONITORING

4.7.7.1 REQUIREMENTS

The Remote Control and Monitoring System (RCMS) must provide a link between the wind turbine and the power dispatcher's control room. This system must serve as a control link, status indicator, and performance monitor. The remote operator must have the capability to command the wind turbine on or off from a remote location and initiate emergency shutdown as warranted. The RCMS should provide the operator with an indication of machine operating conditions and microprocessor status, and indicate significant errors detected by the safety system.

Digital panel meters should provide the operator with the capability of selectively monitoring essential data relating to operation of the wind turbine. In addition, the remote operator should have the capability of starting or stopping the stand alone instrument recorder to record performance data at specified intervals. The RCMS should communicate with the wind turbine via a two telephone pair.

4.7.7.2 APPROACH

The remote control and monitoring system was designed based upon proven technology and utilizing standard, commercially available, off-the-shelf components wherever possible. The panel layout takes into account human engineering to make the RCMS panel operator compatible.

4.7.7.3 SELECTED DESIGN

The RCMS serves as a control link, status indicator, and performance monitor. Interconnection is via two pairs of telephone wires. A single console in the dispatcher's control room could control several wind turbines.

The control functions are limited to on/off command pulses. The primary control function is wind turbine operation which is effected through an interface with the microprocessor. This interface allows the wind turbine to be started or stopped from the dispatcher's control room.

The RCMS is also capable of initiating an emergency shutdown. This allows the dispatcher to shut down the wind turbine in the event that he cannot halt the machine through the microprocessor. Once the machine is halted through the safety system input, it cannot be restarted remotely. The machine must be reset at the site prior to commencing operation. The dispatcher does have the capability of restarting the machine if it is shutdown under microprocessor control.

A series of on/off lights on the RCMS indicate the status of the machine. They display the machine conditions of blades feathered and automatic/manual operation. In addition, six error conditions detectable by the safety system are indicated. The error conditions include overspeed, yaw error, temperature, overcurrent/reverse power, vibration and hydraulic/pneumatic system failures. Status of the microprocessor and stand alone instrument recorder are also indicated.

Performance of the machine is monitored by the analog data section of the RCMS. Six data channels are displayed in digital format. The data channels include wind speed, power, VARS, voltage, current and rotor speed. Any two data channels can be displayed simultaneously with the readouts scaled in engineering units.

Details of the interconnection between the wind turbine site and RCMS are illustrated on NASA Dwg. No. CF759032 (W1016F17). The RCMS consists of a Weston 3200 Series Remote Data Acquisition/Control System as shown on Figure 4.7.7-1.

4.7.8 CONTROL BUILDING

4.7.8.1 REQUIREMENTS

The control building is required to provide a weatherproof enclosure for the low voltage switchgear, control panels and racks and the 48 V battery system.

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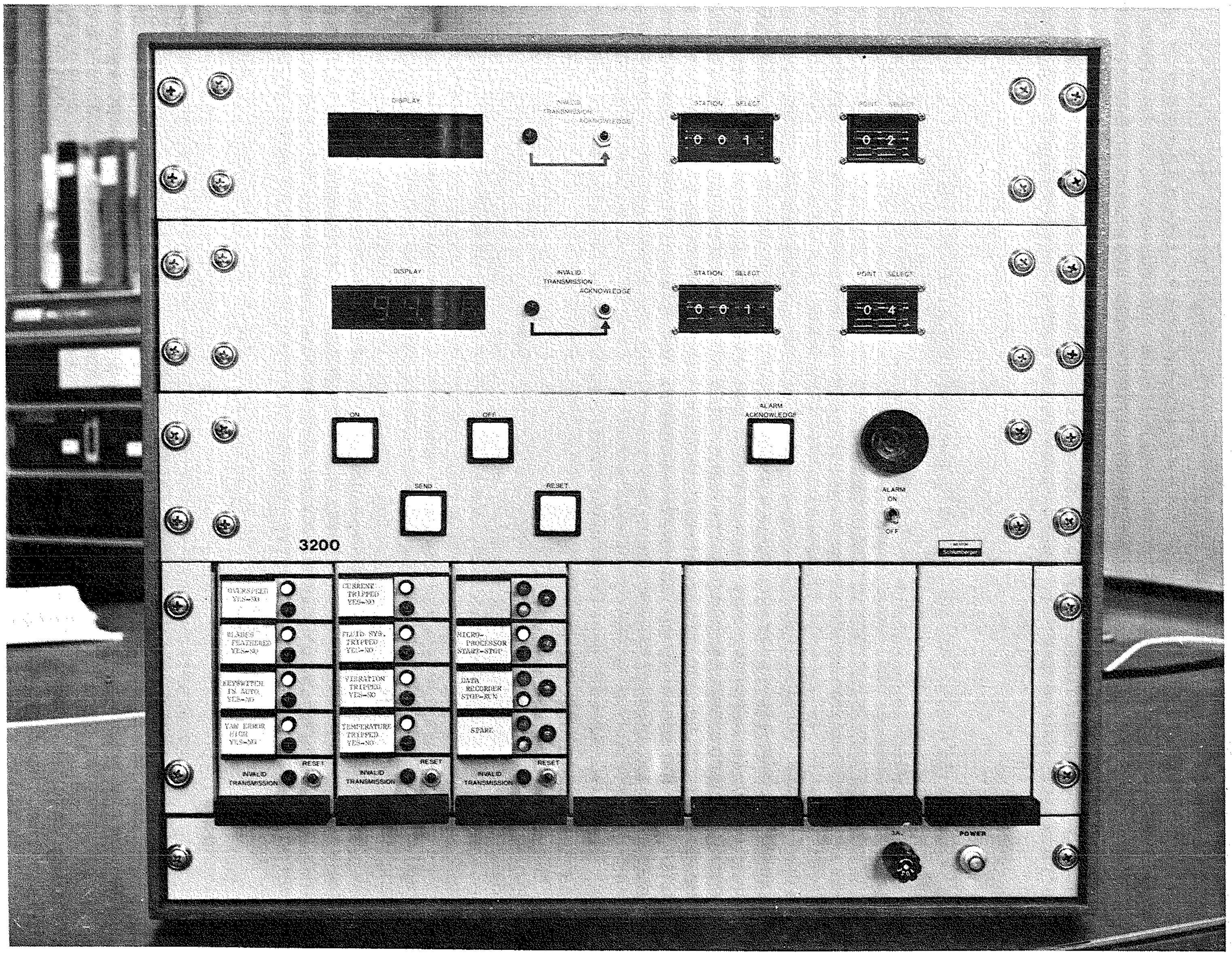


Figure 4.7.7-1. Remote Control and Monitoring System

4.8 SYSTEMS ANALYSIS

4.8.1 DYNAMIC LOADS

The structural design loads presented herein are for the four structural design conditions specified in Section 4.1.1.1.[41] This load set is the basis on which the structural integrity of the blades was predicted. The dynamic analysis was originally performed for MOD-0, and the MOD-0A work is essentially an update. A fixed rotor axis computer program* was utilized to define, in detail, the steady state and cyclic loads acting on the windmill blades. This computer program performs a coupled response analysis that yields spanwise and azimuthal distributions of airloads, bending moments and torsional moments depending on the operational mode selected.

In brief this computer program is a fully coupled aeroelastic blade loads analysis consisting of an aerodynamic performance/trim analysis of a rotor system that is coupled with the dynamic response of the blades. A relaxation type of iterative procedure is employed between the aerodynamics and blade responses to obtain a converged solution that is consistent with the blade mode shape. The aerodynamic portion of the program consists of expressions for rotor thrust, torque, shaft moments, and shaft shear forces utilizing C_l, C_d, and C_m data versus local blade angle of attack, section thickness, and Mach number. An iterative procedure permits one or all of the net rotor forces to be trimmed to describe the operational condition of the rotor in terms of the rotor control angles and/or attitude that is consistent with the response of the blades. The dynamic analysis portion of the program considers the blade response, in harmonic form, to the steady and unsteady airloads, Coriolis forces, gravitational effects and the structural coupling between the flapwise and chordwise bending moments due to collective pitch and local geometric twist angle. The structural model utilizes a finite element description that permits a detail definition of the rotor blade system. This description is unique in that two separate beams are defined to describe one integral rotor blade. The two beams are represented as 1) the feathering blade with provisions for up to 45 stations, and 2) the fixed hub which supports the blade with provisions for up to 31 stations. A total of 44 blade stations are used to represent the windmill blades. This arrangement permits the determination and inclusion, in the net response of the blade, of 1) feather bearing radial forces, 2) feather bearing support elasticity, and 3) kick shear forces resulting from the blade retention mechanism. A quasi-coupled elastic torsion analysis is made where extensive use is made of the output from the basic coupled analysis. The elastic twist angles, as determined in the torsion analysis, are reflected in the aerodynamics of the successive aerostructure cycle in the relaxation process.

Among the many program operating options provided there is one that permits the application of an arbitrary spanwise air loading distribution to the blade structure at any discrete exciting frequency that is an integer multiple of the rotor speed. It is this option that is used to determine the aero-elastic characteristics of the blades for the specified air loads of this concept.

Rotating natural frequencies and mode shapes are computed by the program and utilize the same structural description and inputs as that employed in the

* Code developed by Lockheed

blade loads analysis. This approach ensures the computation of blade frequencies that are directly compatible with computed blade loads.

Natural frequencies for the cantilever blades were computed at various rotor speeds from zero to 50 rpm and at pitch settings, defined at the 3/4 blade radius, of 10°, 0°, and -10°. The results of these calculations for MOD-0 are presented in Figure 4.8.1-1 and show that, for the normal operating speed of 40 rpm, there is adequate separation of the blade frequencies from the aerodynamic excitations at the integer multiples of the rotor speed, nP. Also, the frequency spectrum shows that there is a negligible variation in the frequencies within the blade pitch settings investigated.

The first and lowest mode is 2.76P and it is defined as the first flapping mode where the primary blade motion is normal to the plane of rotation. The second mode is 3.62P and is defined as the first inplane mode with primary blade motions in the rotational plane. The third mode is at 7.57P and shows that the primary motion is again normal to the plane of rotation and it is called the second flapping mode.

The four design conditions are summarized in Table 4.8.1-1. They are described in Section 4.1.1.1 of this report.

For each of the loading cases in Table 4.8.1-1 steady and cyclic, 1P, blade loads were computed. This computation process uses the specified airloads as inputs to obtain the steady state blade bending loads and elastic characteristics. The gravitational effect, due to the spanwise blade mass distribution, is used to define the cyclic blade bending loads and elastic characteristics.

The influence of inplane Coriolis accelerations on cyclic bending loads are obtained independently and superimposed on those due to the gravitational effects. The distribution of the cyclic inplane blade root moment along the span of the blade is accomplished by using a predetermined 1P bending distribution curve. The net spanwise distribution of the cyclic chordwise bending moment is the sum of that due to gravity effects and those due to Coriolis acceleration. The spanwise distribution of the steady state beamwise and chordwise bending moments and inplane and axial shears for the four loading conditions are shown on Figures 4.8.1-2 through Figure 4.8.1-5. Figure 4.8.1-6 presents the net cyclic bending loads for cases 1, 2, and 4 and Figure 4.8.1-7 gives those for case 3. The centrifugal force distribution along the blade span for the nominal rotor speed of 40 rpm is shown on Figure 4.8.1-8.

The wind turbine blades are designed to the aeroelastic loads developed for the four original design conditions. Additional loading conditions were explored to ascertain the influence of various parameters on design loads that may affect the life and reliability of the blades and/or tower. The following conclusions were arrived at:

1. Tower shadow interference has a pronounced effect on the magnitude of cyclic blade bending moments and tower loads depending on size of blockage

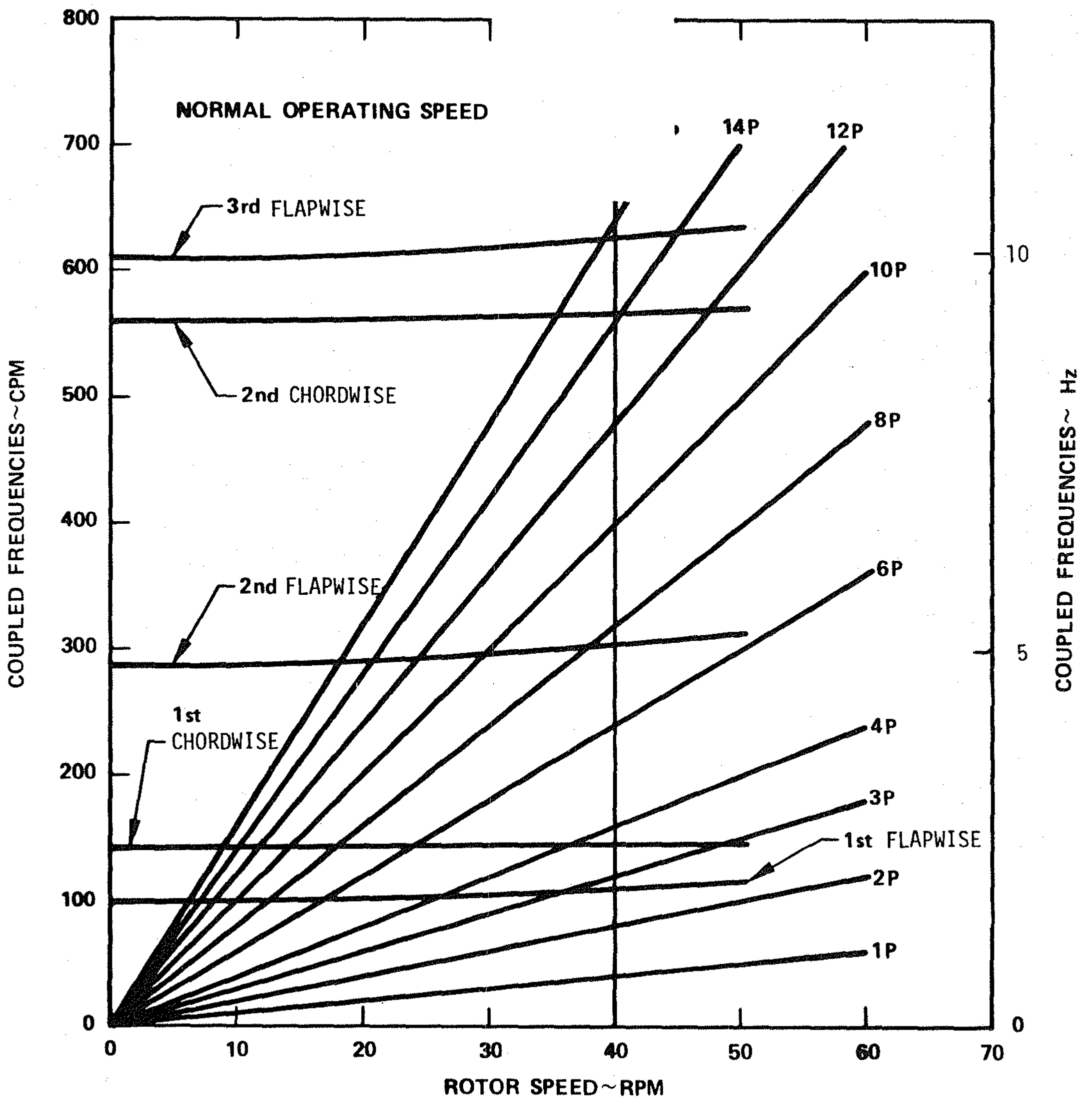


Figure 4.8.1-1. Blade Coupled Frequency Spectrum Cantilever Mode

TABLE 4.8.1-1

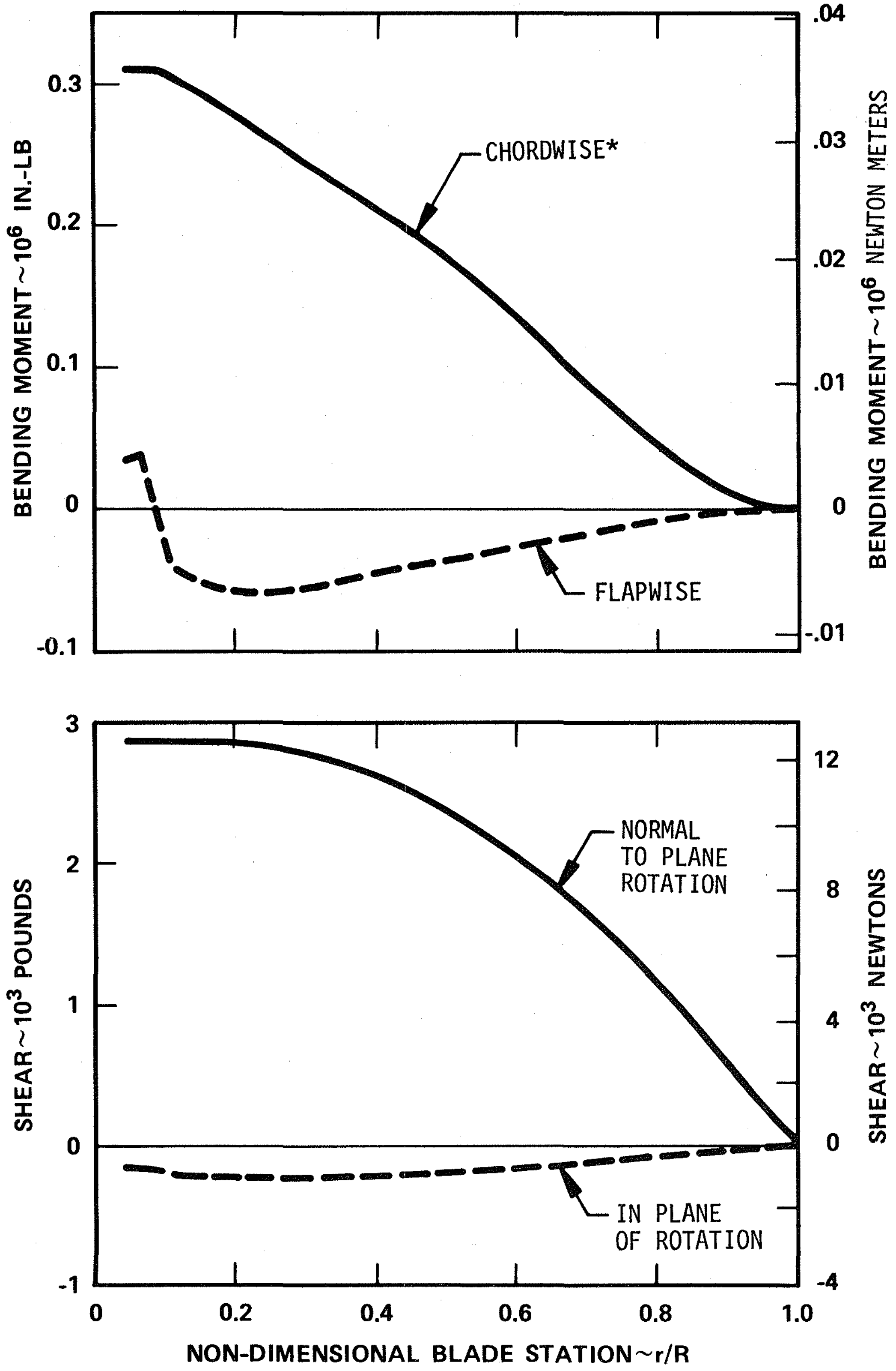
DESIGN CONDITION AS SPECIFIED BY CONTRACT

CASE NO.	BLADE PITCH SETTING @ 3/4 RADIUS	ROTOR SPEED rpm	WIND VELOCITY mph
1	0°	40.	18.
2	0°	40.	60.
3	-90°	40.	18.
4	0°	40.	0.

TABLE 4.8.1-1A

DESIGN CONDITION AS SPECIFIED BY CONTRACT

CASE NO.	BLADE PITCH SETTING @ 3/4 RADIUS	ROTOR SPEED rpm	WIND VELOCITY m/sec
1	0°	40.	8.0
2	0°	40.	26.8
3	-90°	40.	8.0
4	0°	40.	0.0



*MOMENT IN CHORD PLANE

Figure 4.8.1-2. Blade Loads Case 1 ~ Mean Loads

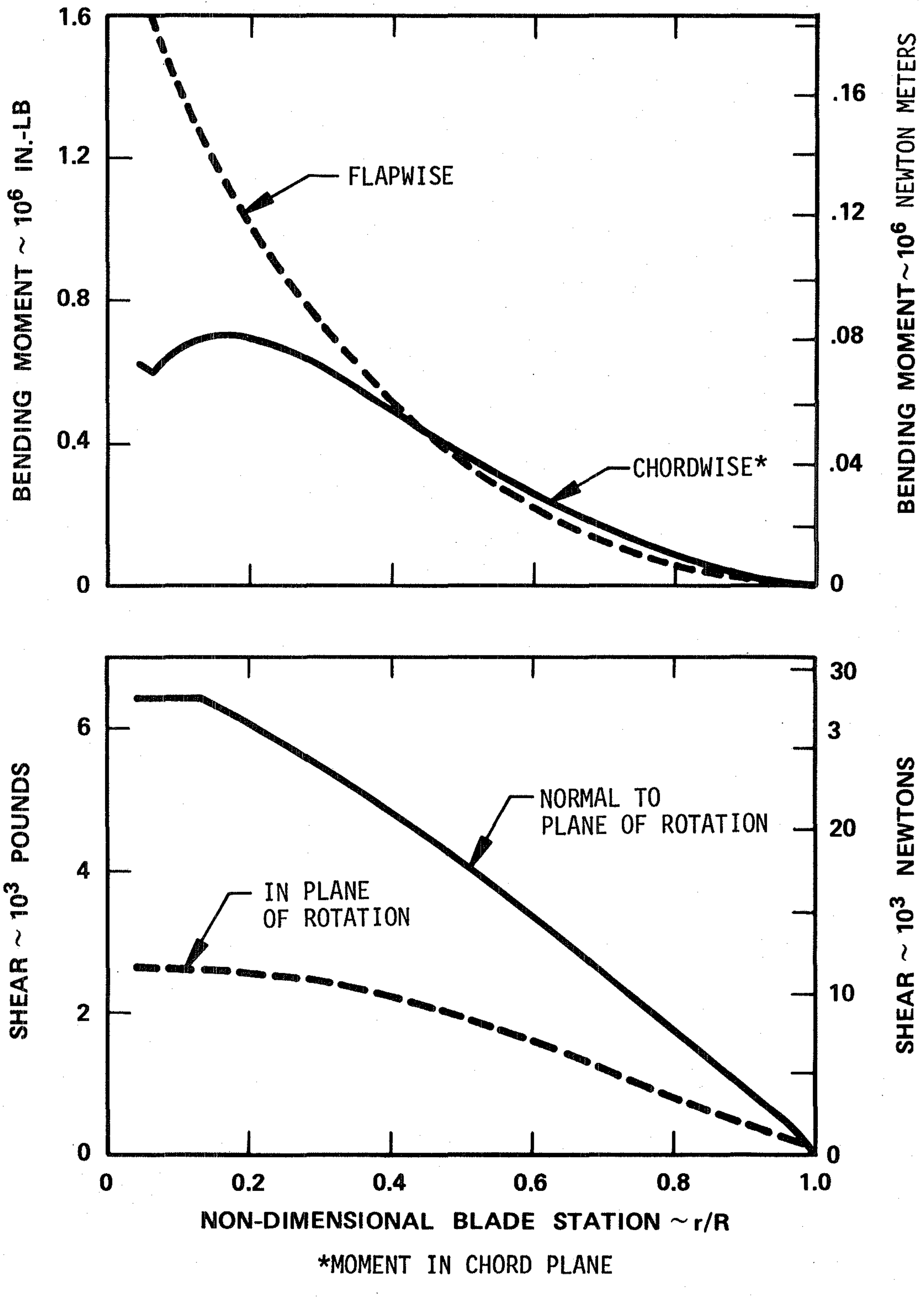


Figure 4.8.1-3. Blade Loads Case 2 ~ Mean Loads

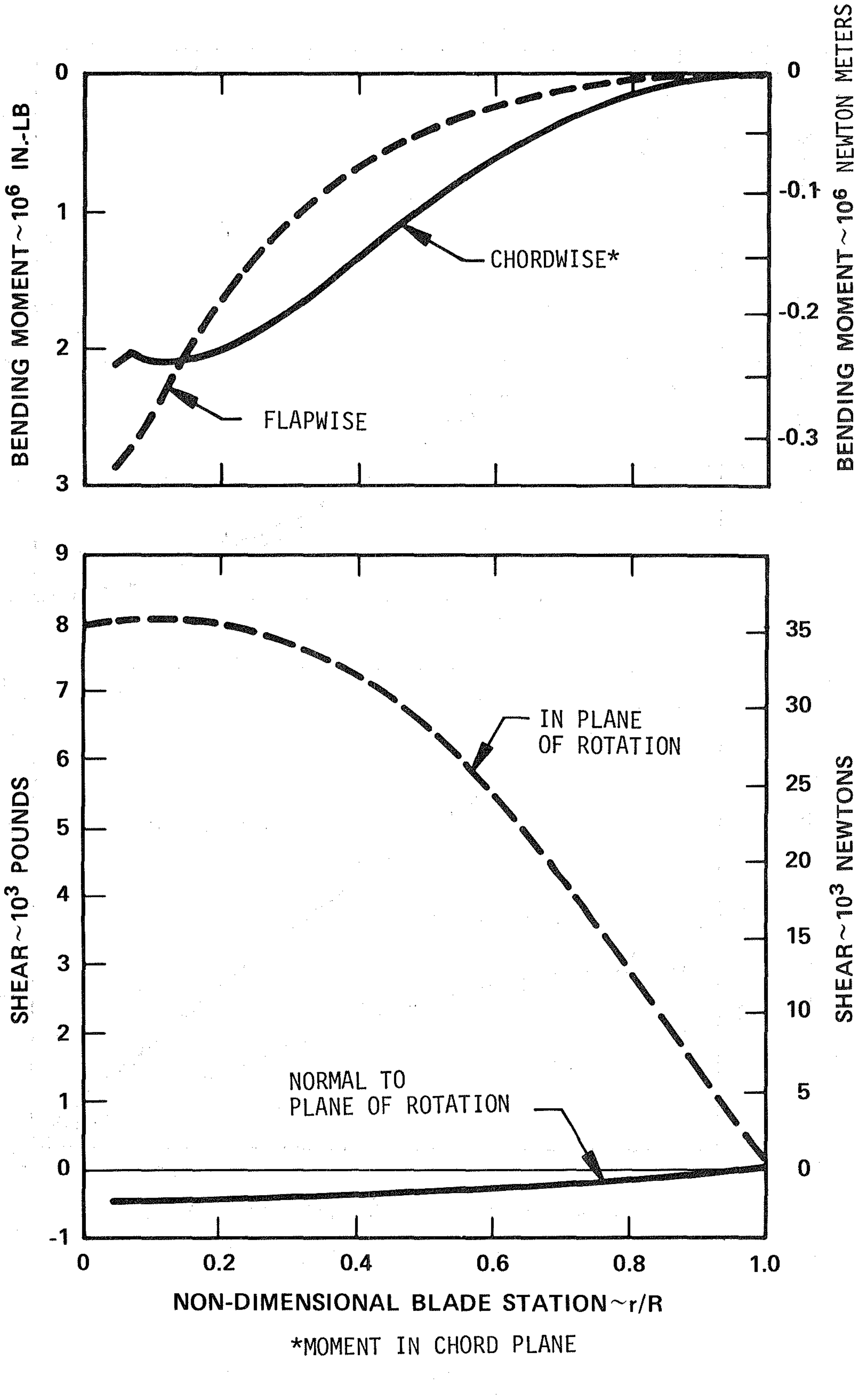
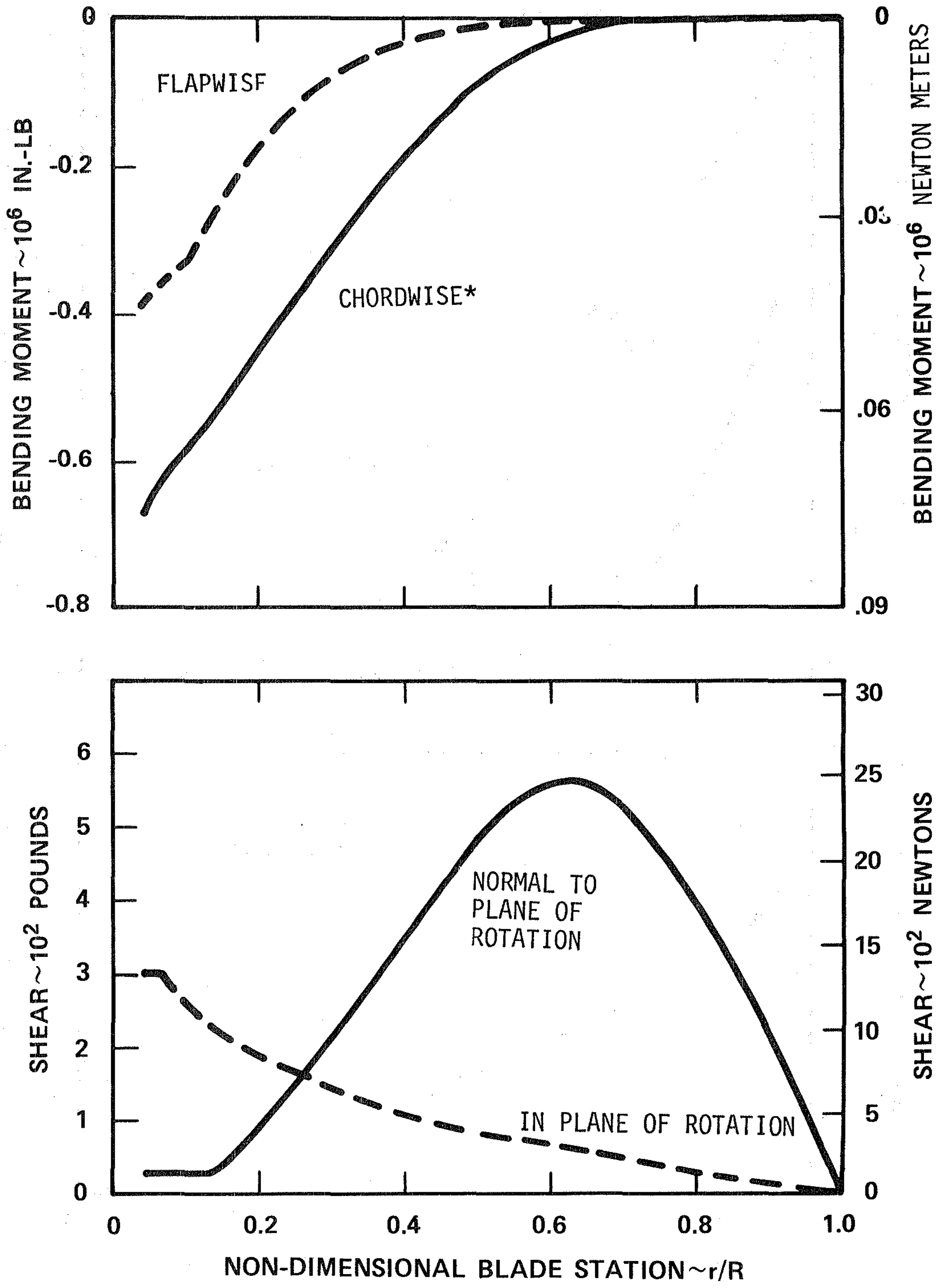


Figure 4.8.1-4. Blade Loads Case 3 ~ Mean Loads



* MOMENT IN CHORD PLANE

Figure 4.8.1-5. Blade Loads Case 4 ∿ Mean Loads

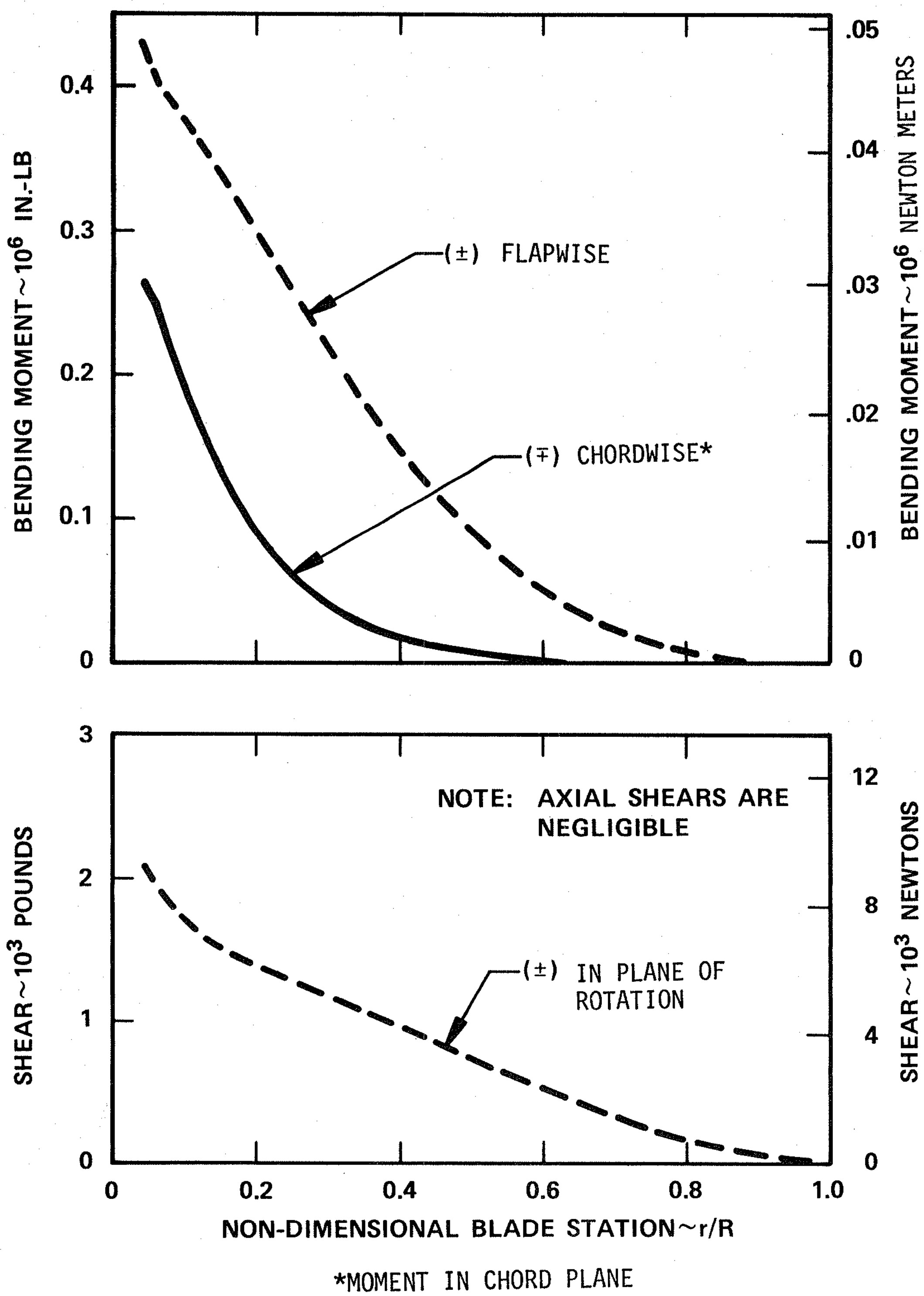


Figure 4.8.1-6. Blade Loads Case 1, 2, and 4 ~ Cyclic Loads

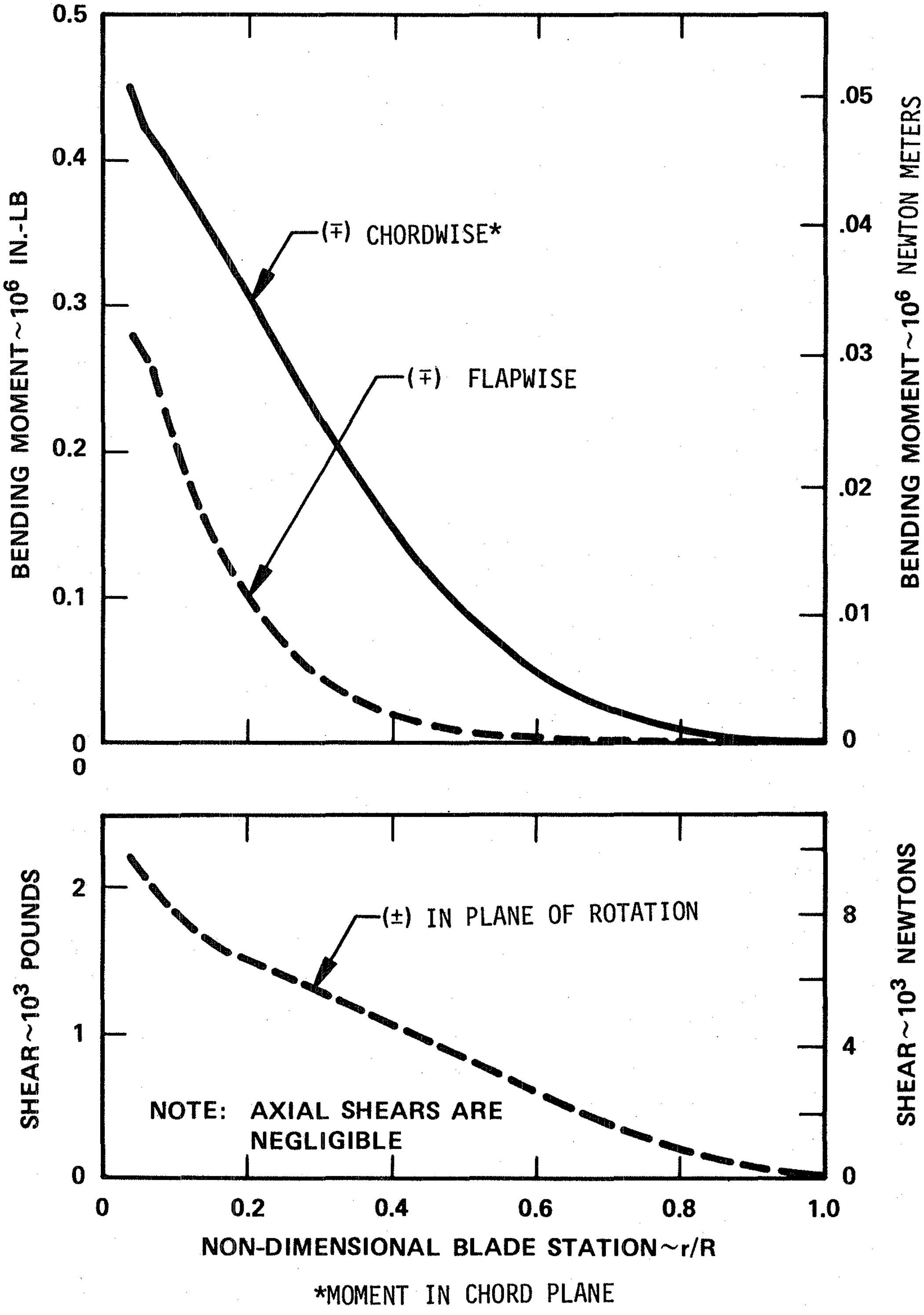


Figure 4.8.1-7. Blade Loads Case 3 ∿ Cyclic Loads

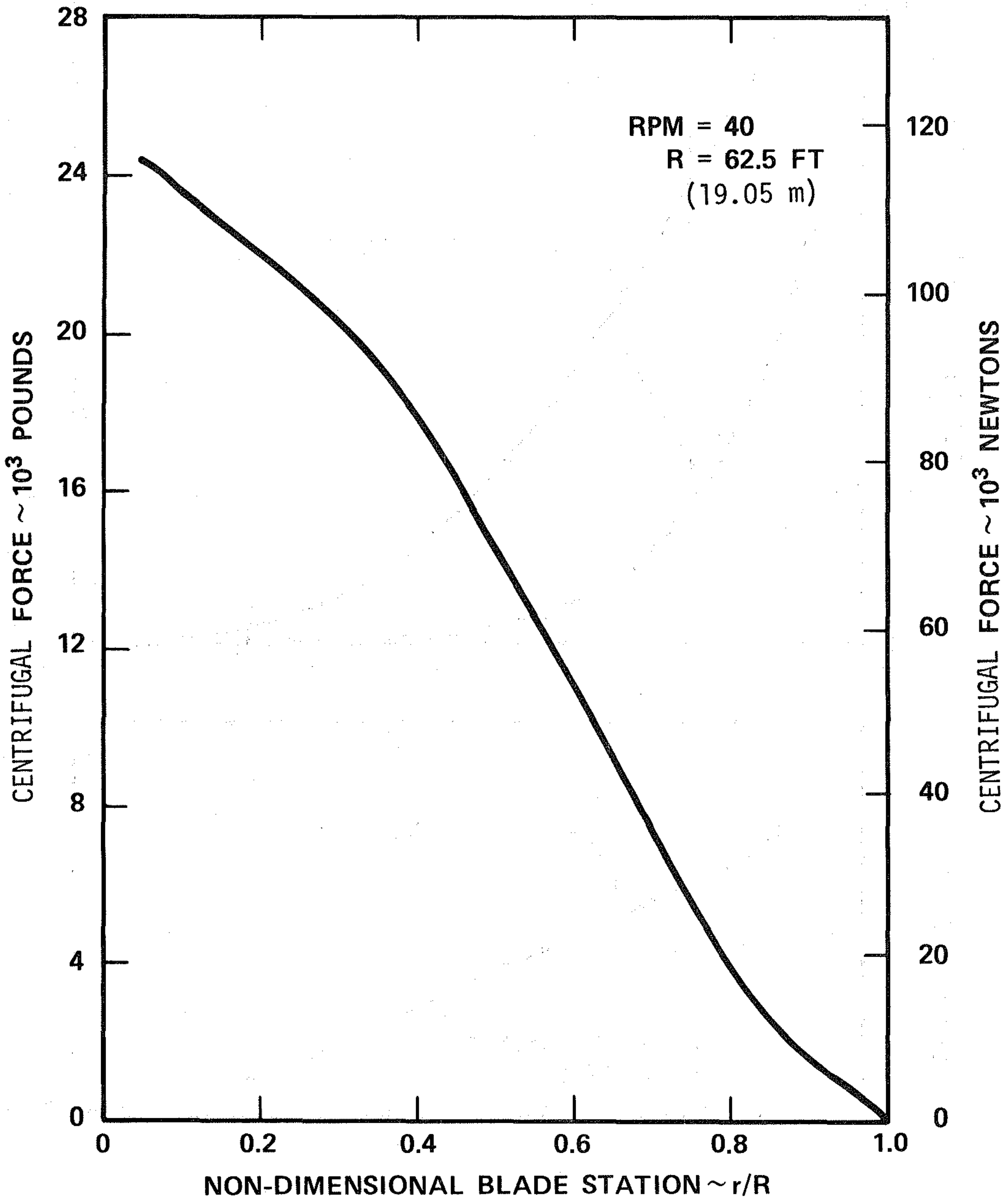


Figure 4.8.1-8. Blade Centrifugal Force

and/or the degree of free stream wind velocity retardation over the rotor sector.

2. Cyclic beamwise bending moments due to tower shadow were shown to increase the baseline cyclic moments used for fatigue analysis. The increase is most significant in the mid span. This loading should be further investigated relative to its effect on fatigue life.

3. Tower shadow tends to reduce the energy extracted from the wind, for a given blade pitch setting, resulting in a less efficient wind energy generator when compared to analysis that ignores the tower.

4. Horizontal ground wind shear results in primarily 1P blade loads and steady and 2P tower loads for a linear wind shear gradient. However, a non-linear wind shear would result in higher frequency blade and tower loads in addition to those experienced for a linear wind shear gradient. This results in larger cyclic loads and will adversely effect the wind energy system.

5. Failure of the yaw control (unable to adjust to the wind direction and/or excess yaw rates) will produce relatively large cyclic blade and tower loads affecting the life of the wind energy system.

As discussed in Section 4.1.1.4, higher loads than these predictions were encountered in MOD-0. Both tower shadow and yaw system problems were found to exist. Modifications were made to the MOD-0 to decrease the shadow and stiffen the yaw system. Figures 4.8.1-9 and 4.8.1-10 summarize the measured and predicted MOD-0 blade loads. After the tower and yaw system modifications were made, the data agreed well with predictions.

This work was updated for MOD-OA. The predicted blade loads are given in Section 4.1.1.4 in Figures 4.1.1-12 and 13. The dynamic analysis produces blade loads at two locations along the length. The detailed loading at other locations is determined from a beam analysis of the blade using the known loads at the two locations.

The loads at numerous interfaces in the WTG are tabulated in Section 4.8.2 where the fatigue analysis is documented. The loads have been computed from the rotor analysis as though the rotor axis is fixed. They have been applied statically to the nacelle and tower for the fatigue work. It has been shown that this approach is conservative.

4.8.2 FATIGUE

Loads were obtained from the WTG dynamic analysis for use in fatigue evaluation of the MOD-OA WTG. Tables 4.8.2-1 through 4.8.2-5 list the specific loads at five key system interfaces. The interface locations are shown in Figure 4.8.2-1. The blade angle listed is clockwise relative to a plumb line looking downwind. All of the fatigue loads are for the worst continuous normal operating condition; 40 mph (18.0 m/s) wind velocity while generating 200 kW of power.

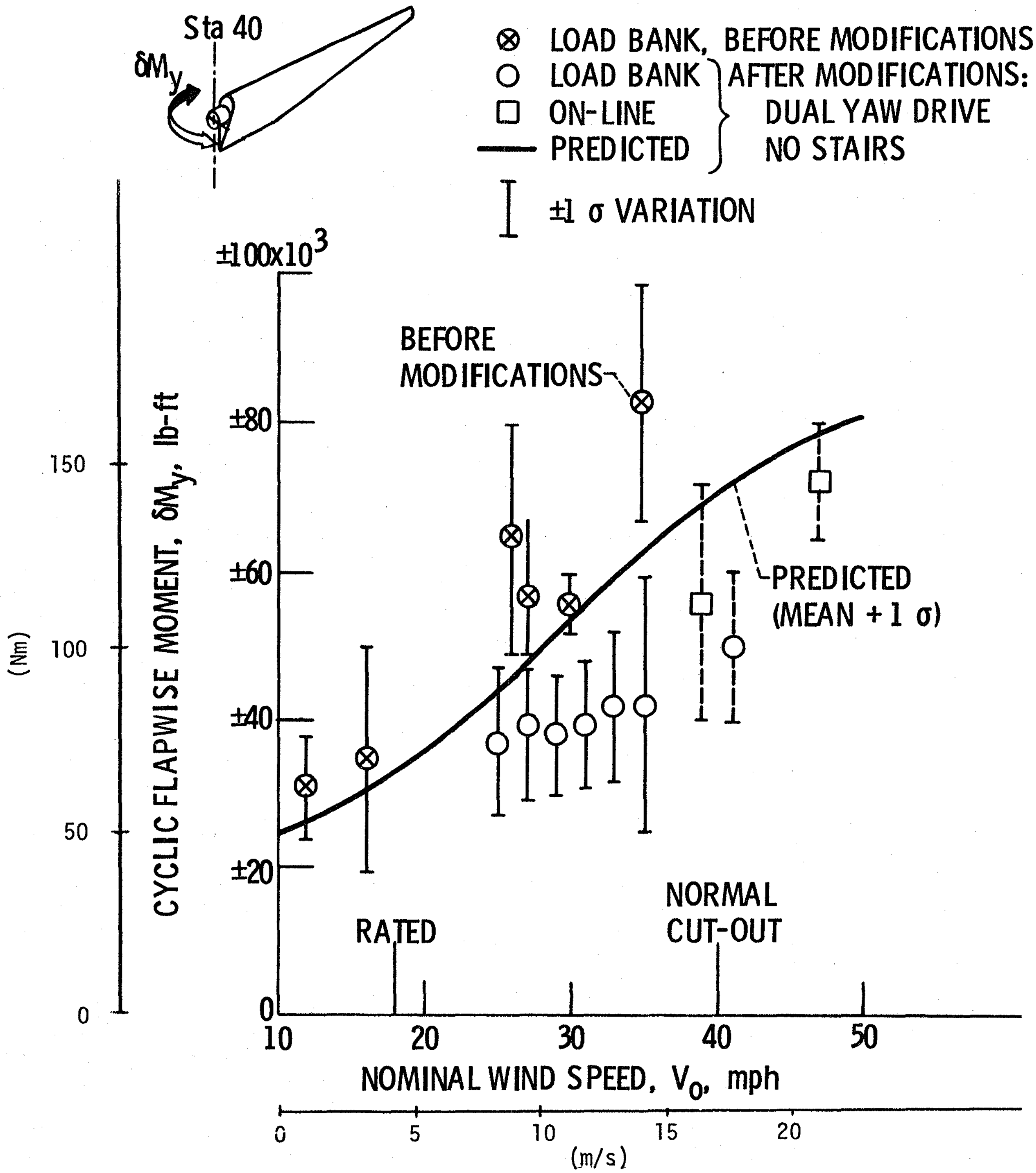


Figure 4.8.1-9 Cyclic Flapwise Bending Loads in MOD-0 Blades Before and After Wind Turbine Modifications

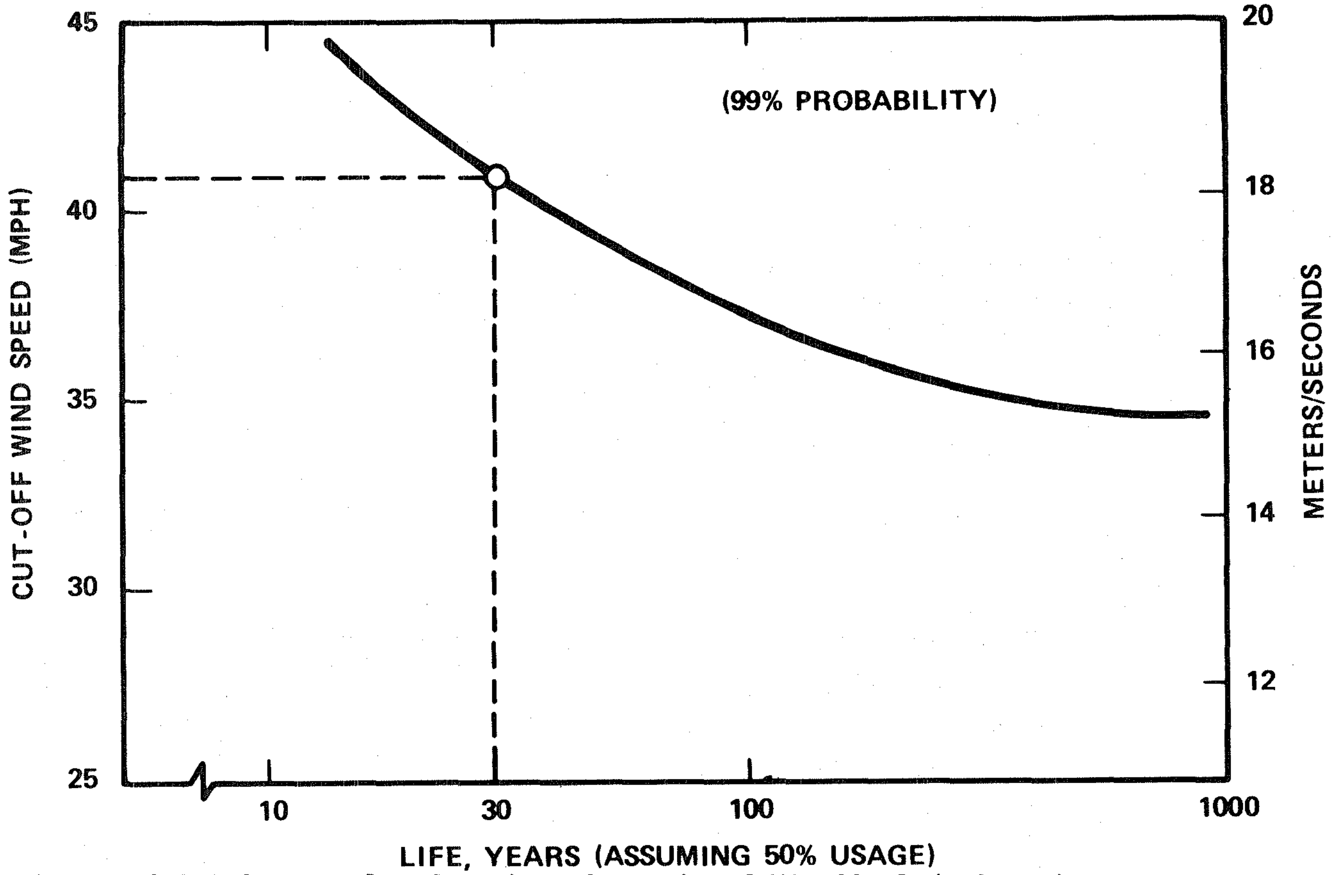


Figure 4.8.2-2. Result of Fatigue Analysis of MOD-OA Blade Assuming Structure Quality Comparable to Airplane Wing Structure

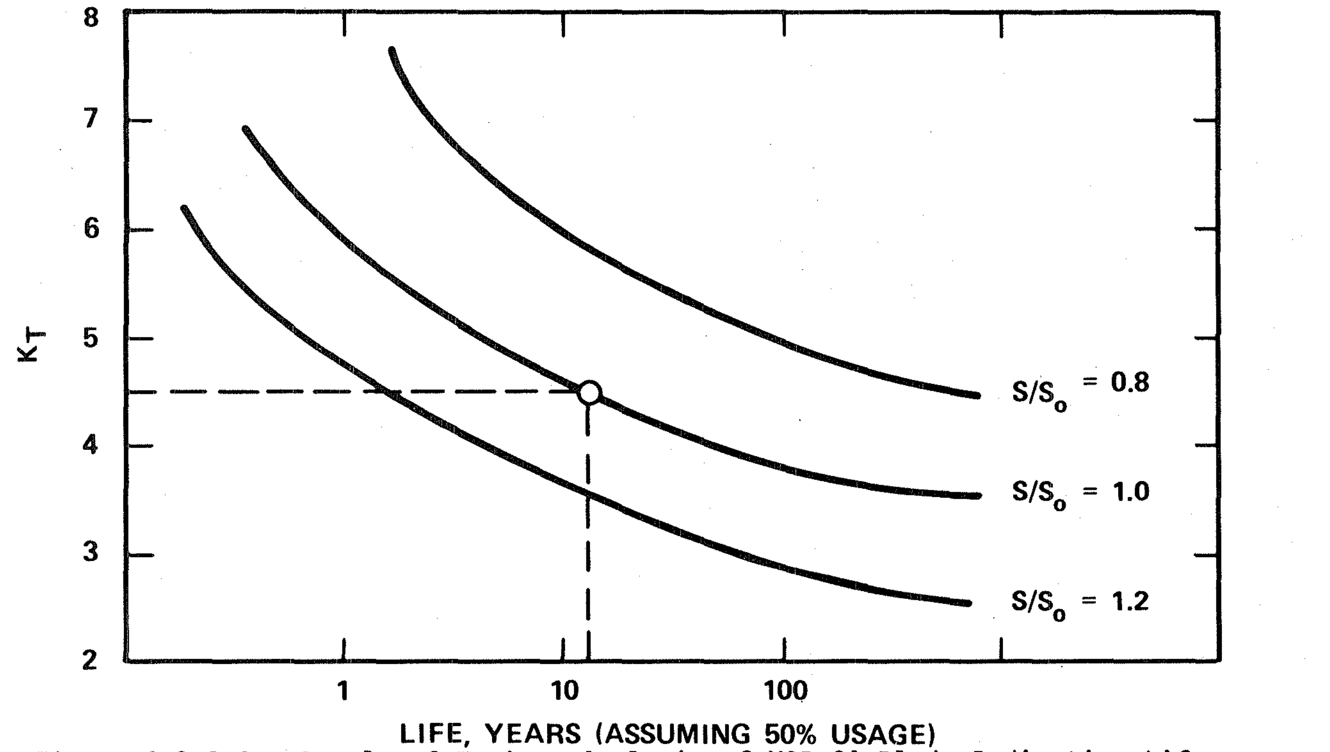


Figure 4.8.2-3. Result of Fatigue Analysis of MOD-OA Blade Indicating Life Predictions as S/S_0 and K_T Vary

4.8.2.1 BLADES

Blade fatigue life prediction entails many uncertainties. For example, there are many situations that might cause the blade loads to exceed the design values, and untested structural details can cause concern regarding blade life prediction even under known load conditions. The curve in Figures 4.8.2-2 shows the results of a fatigue analysis that was made for the MOD-OA blade structure.[51] The analysis assumed:

- Blade station 637.5 is most critical.
- Load distributions as specified above apply.
- The wind turbine will operate at speeds up to the cut-off wind speed for 50 percent of the time.
- The quality of structure (design and manufacture) is comparable to that of an airplane wing, i.e., stress concentrations exist at some local structural details.

The prediction does not consider effects of fretting, corrosion, or other unpredictable damage. The figure shows that a life of 30 years should be attainable with a cut-off wind speed of 41 mph (18.3 m/s).

Many other load reversals can accumulate to damage the structure even though any one separately considered situation would produce loads that fall within ultimate strength limits. Operating conditions that cause load reversals that can accumulate to adversely affect fatigue are:

- Combinations of yaw angle, yaw rates, wind direction, and wind speed;
- Rotor speed and blade pitch setting variations which may cause unanticipated load changes.
- A large number of start-stop cycles
- Nonrotating loads during very high winds.
- Load reversals due to varying amount of tower-flow-through blockage.
- Fluctuations of electrical load demand.
- Frequent actuation of emergency systems.

Results of the fatigue analysis were also plotted (Figure 4.8.2-3) to show what might be expected if

- loads or stresses are different from those calculated, and/or
- the quality of the structure is different from that expected.

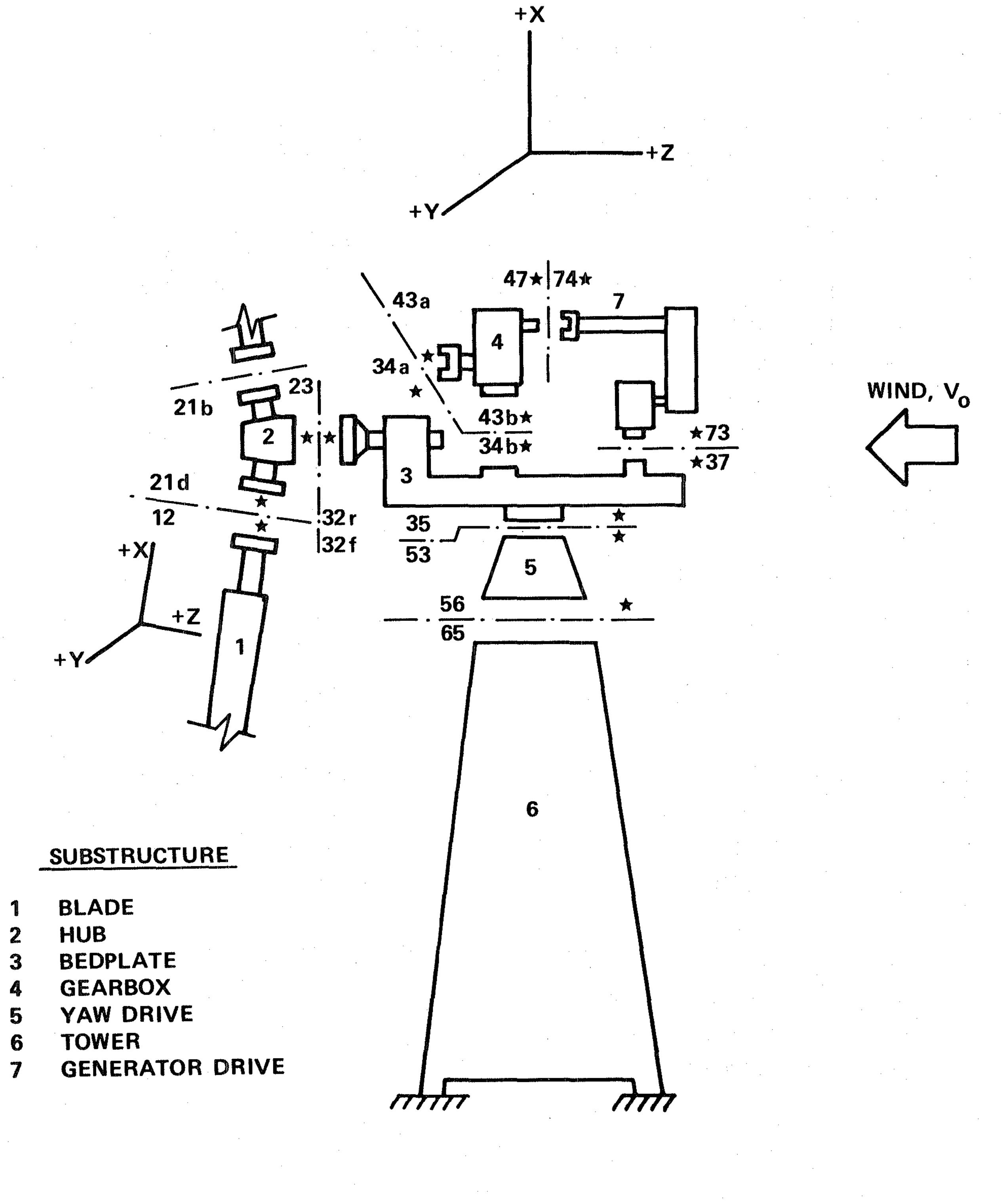


Figure 4.8.2-1. Substructures and Interfaces for Fatigue Analysis of MOD-OA WTG

TABLE 4.8.2-5A

MOD-OA FATIGUE LOADS
Interface 56: Tower loads on yaw drive

BLADE AZIM., ψ, DEG	FORCE LOADS, N VERTICAL F_{x}, 56	LATERAL F_{y}, 56	AXIAL F_{z}, 56	MOMENT LOADS, N m VERTICAL M_{x}, 56	LATERAL M_{y}, 56	AXIAL M_{z}, 56
0	182377	2669	15569	12745	-344785	47996
15	184601	5783	13789	-11796	-387764	73350
30	188160	8452	13345	-38776	-397390	84332
45	188605	5783	15569	-58165	-351292	76875
60	174370	4893	18683	-75790	-246759	52741
75	163250	-5338	20907	-39861	-176121	52741
90	171257	0	21351	4881	-205542	65350
105	187270	-1334	20017	5152	-273604	63723
120	190829	-5338	18683	-10711	-287840	56809
135	182822	-1334	17793	9626	-260724	64944
150	179263	4448	17793	38912	-262080	76061
165	181043	5338	16903	40675	-298958	52606
180	182377	2669	15569	12745	-344785	47996
195	184601	5783	13789	-11796	-387764	73350
210	188160	8452	13345	-38776	-397390	84332
225	188605	5783	15569	-58165	-351292	76875
240	174370	4893	18683	-75790	-246759	52741
255	163250	-5338	20907	-39861	-176121	52741
270	171257	0	21351	4881	-205542	65350
285	187270	-1334	20017	5152	-273604	63723
300	190829	-5338	18683	-10711	-287840	56809
315	182822	-1334	17793	9626	-260724	64944
330	179263	4448	17793	38912	-262080	76061
345	181043	5338	16903	40675	-298958	52606
Steady	177039	1779	17348	-17626	286756	66164
Cyclic	±13789	±7117	±4003	±58300	±110635	±18168
Freq.	2P	2P	2P	2P	2P	2P

TABLE 4.8.2-5

MOD-OA FATIGUE LOADS
Interface 56: Tower loads on yaw drive

BLADE AZIM. ψ, DEG	FORCE LOADS, lb VERTICAL F_x, 56	LATERAL F_y, 56	AXIAL F_z, 56	MOMENT LOADS, ft-lb VERTICAL M_x, 56	LATERAL M_y, 56	AXIAL M_z, 56
0	41000	600	3500	9400	-254300	35400
15	41500	1300	3100	-8700	-286000	54100
30	42300	1900	3000	-28600	-293100	62200
45	42400	1300	3500	-42900	-259100	56700
60	39200	-1100	4200	-55900	-182000	38900
75	36700	-1200	4700	-29400	-129900	38900
90	38500	0	4800	3600	-151600	48200
105	42100	-300	4500	3800	-201800	47000
120	42900	-1200	4200	-7900	-212300	41900
135	41100	300	4000	7100	-192300	47900
150	40300	-1000	4000	28700	-193300	56100
165	40700	-1200	3800	30000	-220500	38800
180						
195						
210						
225						
240						
255			REPEAT ABOVE			
270						
285						
300						
315						
330						
345						
Steady	39800	400	3900	-1300	-211500	48800
Cyclic	±3100	±1600	±900	±43000	±81600	±13400
Freq.	2P	2P	2P	2P	2P	2P

TABLE 4.8.2-4A

MOD-OA FATIGUE LOADS
Interface 35: Yaw drive loads on bedplate

BLADE AZIM., ψ_b, DEG	FORCE LOADS, N VERTICAL $F_{x,35}$	LATERAL $F_{y,35}$	AXIAL $F_{z,35}$	MOMENT LOADS, N-m VERTICAL $M_{x,35}$	LATERAL $M_{y,35}$	AXIAL $M_{z,35}$
0	177929	2669	15569	12745	-328649	45420
15	180153	5783	13789	-11796	-373257	67249
30	183712	8452	13345	-38776	-383425	75655
45	184156	5783	15569	-58165	-335023	70774
60	169922	4893	18683	-75790	-227100	58029
75	158802	-5338	20907	-39861	-167850	58165
90	166808	0	21351	4881	-169884	65350
105	182822	-1334	20017	5152	-252724	65079
120	186381	-5338	18683	-10711	-268316	61012
135	178374	-1334	17793	9626	-242285	65079
150	174815	4448	17793	38912	-243776	71316
165	176594	5338	16903	40675	-281197	46098
180	177929	2669	15569	12745	-328649	45420
195	180153	5783	13789	-11796	-373257	67249
210	183712	8452	13345	-38776	-383425	75655
225	184156	5783	15569	-58165	-335023	70774
240	169922	4893	18683	-75790	-227100	58029
255	158802	-5338	20907	-39861	-167850	58165
270	166808	0	21351	4881	-169884	65350
285	182822	-1334	20017	5152	-252724	65079
300	186381	-5338	18683	-10711	-268316	61012
315	178374	-1334	17793	9626	-242285	65079
330	174815	4448	17793	38912	-243776	71316
345	176594	5338	16903	40675	-281197	46098
Steady	172591	1779	17348	-17626	-275638	60469
Cyclic	±13789	±7117	±4003	±58300	±107788	±15185
Freq.	2P	2P	2P	2P	2P	2P

TABLE 4.8.2-4

MOD-OA FATIGUE LOADS
Interface 35: Yaw drive loads on bedplate

BLADE AZIM., ψ_b, DEG	FORCE LOADS, lb VERTICAL $F_{x,35}$	LATERAL $F_{y,35}$	AXIAL $F_{z,35}$	MOMENT LOADS, ft-lb VERTICAL $M_{x,35}$	LATERAL $M_{y,35}$	AXIAL $M_{z,35}$
0	40000	600	3500	9400	-242399	33500
15	40500	1300	3100	-8700	-275300	49600
30	41300	1900	3000	-28600	-282800	55800
45	41400	1300	3500	-42900	-247100	52200
60	38200	-1100	4200	-55900	-167500	42800
75	35700	-1200	4700	-29400	-123800	42900
90	37500	0	4800	3600	-125300	48200
105	41100	-300	4500	3800	-186400	48000
120	41900	-1200	4200	-7900	-197900	45000
135	40100	-300	4000	7100	-178700	48000
150	39300	1000	4000	28700	-179800	52600
165	39700	1200	3800	30000	-207400	34000
180						
195						
210						
225						
240						
255			REPEAT ABOVE			
270						
285						
300						
315						
330						
345						
Steady	38800	400	3900	-13000	-203300	44600
Cyclic	±3100	±1600	±900	±43000	±79500	±11200
Freq.	2P	2P	2P	2P	2P	2P

TABLE 4.8.2-3A

MOD-OA FATIGUE LOADS

BLADE AZIM., ψ_b, DEG	BED PLATE $M_{z,34a}$	AXIAL MOMENT LOADS, N m (ALL OTHERS ZERO)						
		GEARBOX			GEN. DRIVE		BEDPLATE	
		$M_{z,34a}$	$M_{z,43b}$	$M_{z,47}$	$M_{z,74}$	$M_{z,73}$	$M_{z,34b}$	$M_{z,37}$
0	42573	-42573	43522	-963	963	-963	-43522	963
15	70638	-70638	72265	-1600	1600	-1600	-72265	1505
30	66300	-66300	67791	-1505	1505	-1505	-67791	1505
45	64130	-64130	65622	-1464	1464	-1464	-65622	1464
60	63723	-63723	65079	-1451	1451	-1451	-65079	1451
75	63995	-63995	65486	-1451	1451	-1451	-65486	1451
90	65350	-65350	66842	-1505	1505	-1505	-66842	1505
105	66571	-66571	68062	-1505	1505	-1505	-66062	1505
120	66977	-66977	68469	-1519	1519	-1519	-68469	1519
135	66571	-66571	68062	-1505	1505	-1505	-68062	1505
150	66164	-66164	67655	-1505	1505	-1505	-67655	1505
165	41352	-41352	42166	-936	936	-936	-42166	936
180	42573	-42573	43522	-963	963	-963	-43522	963
195	70638	-70638	72265	-1600	1600	-1600	-72265	1600
210	66300	-66300	67791	-1505	1505	-1505	-67791	1505
225	64130	-64130	65622	-1464	1464	-1464	-65622	1464
240	63723	-63723	65079	-1451	1451	-1451	-65079	1451
255	63995	-63995	65486	-451	1451	-1451	-65486	1451
270	65350	-65350	66842	-1505	1505	-1505	-66842	1505
285	66571	-66571	68062	-1505	1505	-1505	-68062	1505
300	66977	-66977	68469	-1519	1519	-1519	-68469	1519
315	66571	-66571	68062	-1505	1505	-1505	-68062	1505
330	66164	-66164	67655	-1505	1505	-1505	-67655	1505
345	41352	-41352	42166	-936	936	-936	-42166	936
Steady	55995	-55995	57216	-1274	1274	-1274	-57216	1274
Cyclic	±14643	±14643	±15050	±325	±325	±325	±15050	325
Freq.	2P	2P	2P	2P	2P	2P	2P	2P

TABLE 4.8.2-3

MOD-OA FATIGUE LOADS

BLADE AZIM., ψ_b, DEG	BED PLATE M_z, 34a	AXIAL MOMENT LOADS, ft-lb (ALL OTHERS ZERO)						
		GEARBOX			GEN. DRIVE		BEDPLATE	
		M_z, 34a	M_z, 43b	M_z, 47	M_z, 74	M_z, 73	M_z, 34b	M_z, 37
0	31400	-31400	32100	-710	710	-710	-32100	710
15	52100	-52100	53300	-1180	1180	-1180	-53300	1180
30	48900	-48900	50000	-1110	1110	-1110	-50000	1110
45	47300	-47300	48400	-1080	1080	-1080	-48400	1080
60	47000	-47000	48000	-1070	1070	-1070	-48000	1070
75	47200	-47200	48300	-1070	1070	-1070	-48300	1070
90	48200	-48200	49300	-1100	1100	-1100	-49300	1100
105	49100	-49100	50200	-1110	1110	-1110	-50200	1110
120	49400	-49400	50500	-1120	1120	-1120	-50500	1120
135	49100	-49100	50200	-1110	1110	-1110	-5020	1110
150	48800	-48800	49900	-1110	1110	-1110	-49900	1110
165	30500	-30500	31100	-690	690	-690	-31100	690
180								
195								
210								
225								
240								
255			REPEAT	ABOVE				
270								
285								
300								
315								
330								
345								
Steady	41300	-41300	42200	-940	940	-940	-42200	940
Cyclic	±10800	±10800	±11100	±240	±240	±240	±11100	±240
Freq.	2P	2P	2P	2P	2P	2P	2P	2P

TABLE 4.8.2-2A

MOD-OA FATIGUE LOADS
Interface 23: Shaft Loads on hub

BLADE AZIM., ψ_b, DEG	FORCE LOADS, N RADIAL $F_{x,23}$	LATERAL $F_{y,23}$	AXIAL $F_{z,23}$	MOMENT LOADS, N-m RADIAL $M_{x,23}$	LATERAL $M_{y,23}$	AXIAL $M_{z,23}$
0	57827	2669	15569	5152	-153614	42573
15	56492	21351	13789	21286	-194018	70638
30	50710	39144	13345	41217	-199848	66300
45	41368	49375	15569	45827	-153343	64130
60	29358	40479	18683	32675	-88535	63723
75	15124	36031	20907	25083	-31455	63995
90	0	46706	21351	36336	-4881	65350
105	-15124	60941	20017	53012	23727	66571
120	-28469	60051	18683	53012	37014	66977
135	-40479	42258	17793	34980	54504	66571
150	-49375	23131	17793	16677	78773	66164
165	-55603	9786	16903	4203	112126	41352
180	-57827	-2669	15569	-5152	153614	42573
195	-56942	-21351	13789	-21286	194018	70638
210	-50710	-39144	13345	-41217	199848	66300
225	-41368	-49375	15569	-45827	153343	64130
240	-29358	-40479	18683	-32675	88535	63723
255	-15124	-36031	20907	-25083	31455	63995
270	0	-46706	21351	-36336	-4881	65350
285	41368	-60941	20017	-53012	-23727	66571
300	28469	-60051	18683	-53012	-37014	66977
315	40479	-42258	17793	-34980	-54504	66571
330	49375	-23131	17793	-16677	-78773	66164
345	55603	-9786	16903	-4203	-112126	41352
Steady	0	0	17348	0	0	55995
Cyclic	±57827	±60941	±4003	±53012	±199848	±14643
Freq.	1P	1P	2P	1P	1P	2P

TABLE 4.8.2-2

MOD-OA FATIGUE LOADS
Interface 23: Shaft Loads on hub

BLADE AZIM., ψ_b, DEG	FORCE LOADS, lb RADIAL $F_{x,23}$	LATERAL $F_{y,23}$	AXIAL $F_{z,23}$	MOMENT LOADS, ft-lb RADIAL $M_{x,23}$	LATERAL $M_{y,23}$	AXIAL $M_{z,23}$
0	13000	600	3500	3800	-113300	31400
15	12700	4800	3100	15700	-143100	52100
30	11400	8800	3000	30400	-147400	48900
45	9300	11100	3500	33800	-113100	47300
60	6600	9100	4200	24100	-65300	47000
75	3400	8100	4700	18500	-23200	47200
90	0	10500	4800	26800	-3600	48200
105	-3400	13700	4500	39100	17500	49100
120	-6400	13500	4200	39100	27300	49400
135	-9100	9500	4000	25800	40200	49100
150	-11100	5200	4000	12300	58100	48800
165	-12500	2200	3800	3100	82700	30500
180	-13000	-600	3500	-3800	113300	31400
195	-12700	-4800	3100	-15700	143100	52100
210	-11400	-8800	3000	-30400	147400	48900
225	-9300	-11100	3500	-33800	113100	47300
240	-6600	-9100	4200	-24100	65300	47000
255	-3400	-8100	4700	-18500	23200	47200
270	0	-10500	4800	-26800	-3600	48200
285	3400	-13700	4500	-39100	-17500	49100
300	6400	-13500	4200	-39100	-27300	49400
315	9100	-9500	4000	-25800	-40200	49100
330	11100	-5200	4000	-12300	-58100	48800
345	12500	-2200	3800	-3100	-82700	30500
Steady	0	0	3900	0	0	41300
Cyclic	±13000	±13700	±900	±39100	±147400	±10800
Freq.	1P	1P	2P	1P	1P	2P

TABLE 4.8.2-1A

MOD-OA FATIGUE LOADS
Interface 12: Hub loads on blade

BLADE AZIM., ψ_b, DEG	FORCE LOADS, N RADIAL F_x	LATERAL F_y	AXIAL F_z	MOMENT LOADS, N m RADIAL M_x	LATERAL M_y	AXIAL M_z
0	136560	-1334	-14234	0	-119040	2305
15	136560	1779	-16458	-1220	-150903	-19524
30	135671	4448	-16903	-470	-159987	-58029
45	133891	8452	-13789	-542	-128667	-50843
60	132112	890	-8896	-271	-85145	-3932
75	128998	-3114	-6228	0	-50843	24676
90	126330	1779	-4448	0	-35929	-2576
105	123661	9341	-4448	-136	-36452	-49487
120	121436	10676	-4893	-136	-41488	-55860
135	119212	4448	-4893	0	-41352	-17083
150	117433	-1334	-4003	136	-33218	19388
165	116099	-2669	-2669	136	-19660	27523
180	116099	-4003	-1334	0	-6644	36336
195	116099	-10231	-445	0	407	74434
210	117433	-16458	-890	136	-136	115108
225	119212	-16014	-1779	136	-6915	109279
240	120992	-8896	-2669	0	-17626	61961
255	123661	-4448	-4003	0	-29015	33624
270	126330	-9341	-4893	271	-40403	62096
285	128998	-17348	-6228	542	-50843	110092
300	131667	-18683	-7562	678	-61147	116872
315	133891	-12455	-8452	542	-71316	77688
330	135671	-6672	-9341	271	-80943	40946
345	1365	2669	-11565	136	-94636	9897
Steady	126330	-4003	-8896	-271	-79722	29421
Cyclic	±10231	±14679	±8007	±949	±80264	87450
Freq.	1P	1P	1P	1P	1P	1P

TABLE 4.8.2-1

MOD-OA FATIGUE LOADS
Interface 12: Hub loads on blade

BLADE AZIM., ψ_b, DEG	FORCE LOADS, lb RADIAL F_x	LATERAL F_y	AXIAL F_z	MOMENT LOADS, ft-lb RADIAL M_x	LATERAL M_y	AXIAL M_z
0	30700	-300	-3200	0	-87800	1700
15	30700	400	-3700	-900	-111300	-14400
30	30500	1000	-3800	-300	-118000	-42800
45	30100	1900	-3100	-400	-94900	-37500
60	29700	200	-2100	-200	-62800	-2900
75	29000	-700	-1400	0	-37500	18200
90	28400	400	-1000	0	-26500	-1900
105	27800	2100	-1000	-100	-26900	-36500
120	27300	2400	-1100	-100	-30600	-41200
135	26800	1000	-1100	0	-30500	-12600
150	26400	-300	-900	100	-24500	14300
165	26100	-600	-600	100	-14500	20300
180	26100	-900	-300	0	-4900	26800
195	26100	-2300	-100	0	300	54900
210	26400	-3700	-200	100	-100	84900
225	26800	-3600	-400	100	-5100	80600
240	27200	-2000	-600	0	-13000	45700
255	27800	-1000	-900	0	-21400	24800
270	28400	-2100	-1100	200	-29800	45800
285	29000	-3900	-1400	400	-37500	81200
300	29600	-4200	-1700	500	-45100	86200
315	30100	-2800	-1900	400	-52600	57300
330	30500	-1500	-2100	200	-59700	30200
345	30700	600	-2600	100	-69800	7300
Steady	28400	-900	-2000	-200	-58800	21700
Cyclic	±2300	±3300	±1800	±700	±59200	±64500
Freq.	1P	1P	1P	1P	1P	1P

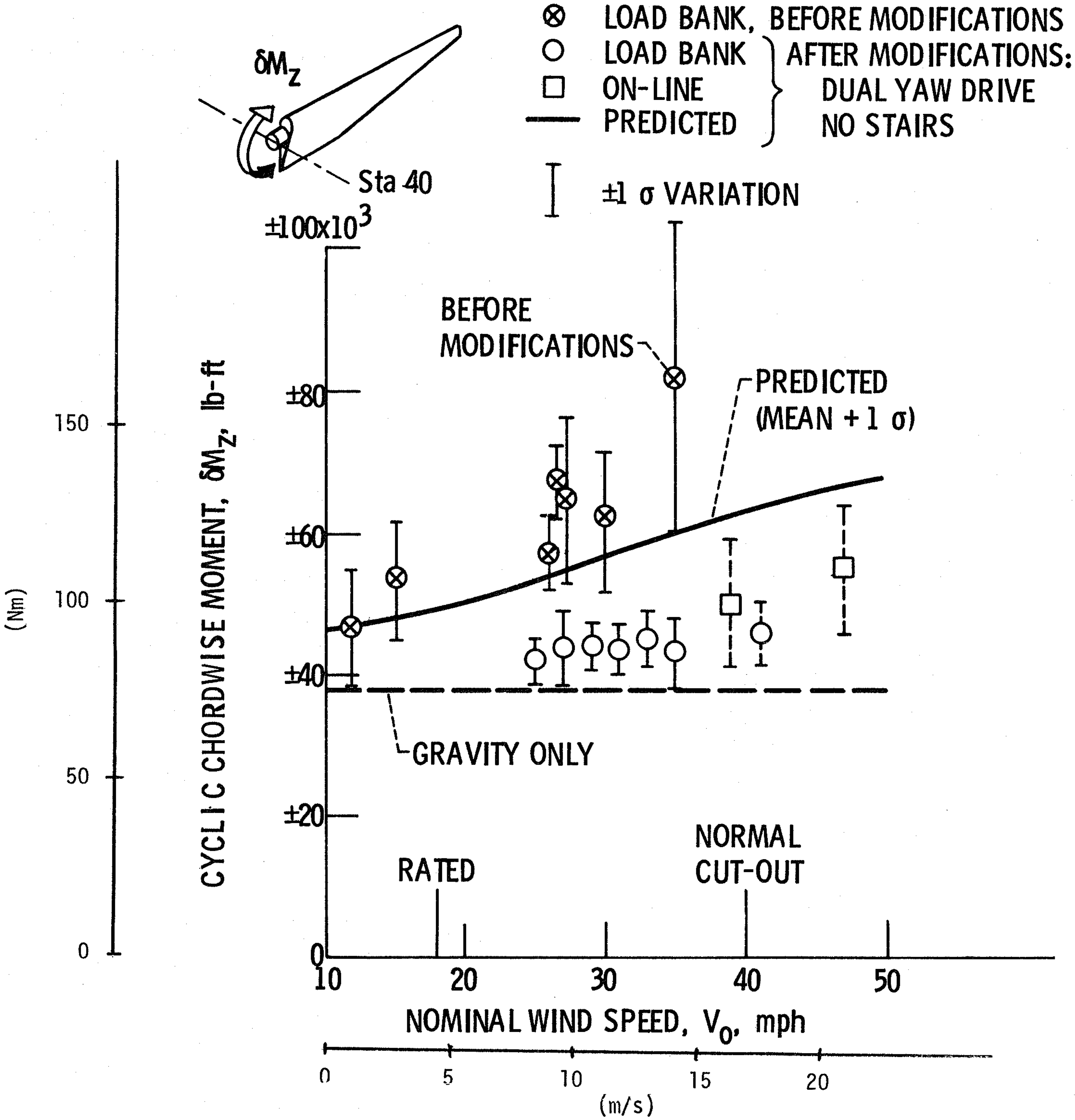


Figure 4.8.1-10 Cyclic Chordwise Bending Loads in MOD-0 Blades Before and After Wind Turbine Modifications

Interpretation of Figure 4.8.2-3 requires definition of two symbols which are common to fatigue analysis, S/S_o and K_T. S represents stress, and the subscript, o, merely signifies "original"; so $S/S_o = 1.0$ represents the values used in the analysis whereas a ratio above 1.0 would indicate that actual stresses will be greater than those used in the analysis. The K_T value is a measure of the quality of the structure; it reflects holes, scratches, cut-outs, etc. A value of $K_T = 4.5$ is representative of the quality of aircraft structure generally sought during design, but as implied earlier, it's not unusual for K_T values to be as high as six or seven at some structural details.

It's noteworthy from both Figures (4.8.2-2 and 3) that a change of a few mph of cut-off wind speed, or a small change in either K_T or S/S_o, can mean a change of very many years of life. Tests of structural details could significantly reduce the uncertainty of fatigue life prediction but were not considered cost-effective considering the experimental/demonstration nature of MOD-OA. Close monitoring of blade performance and condition will be provided.

4.8.2.2 LOW SPEED SHAFT

The low speed shaft diameter is set by the bearings that were selected. The critical stress point is the fillet on the rotor side of the downwind bearing. Based on nominal shaft diameter under normal operating conditions, the mean shaft stress is 2244 psi (15.5 MPa) and the alternating stress is 8057 psi (55.6 MPa). The fatigue strength of the 4340 steel shaft is a function of the fillet stress concentration factor, (K_T). The K_T value estimated for the shaft is 2.7 giving an endurance stress level of .19 times the ultimate stress of the shaft material. The ultimate is estimated at 105,000 psi (724 MPa) giving an allowable alternating stress of 19950 psi (138 MPa). Thus the shaft is adequate under normal operation. Off design and transient conditions, however, were not evaluated.

4.8.2.3 LOW SPEED SHAFT BEARINGS AND CAPS

The loads at the bearings are listed below. Bearing A is the upwind bearing

BEARING LOADS

BEARING	THRUST lbs (N)	VERTICAL lbs (N)	SIDE lbs (N)
A		9390 + 5796	3645 + 3243
		(41,764 ∓ 25,779)	(16,212 + 14,424)
B	3870 + 880	20856 ∓ 8607	3423 + 2988
	(17,212 ∓ 3,914)	(92,760 ∓ 38,281)	(15,224 ± 13,290)

and bearing B, the downwind bearing. The bearings are Torrington No. 260SD32 which have a static load capacity of 670,000 lbs (3,000,000 N) and a dynamic capacity of 531,700 lbs (2,400,000 N) for 10^6 cycles. These bearings should have a near infinite life under the tabulated MOD-OA loadings.

A detailed analysis of the bearing caps was performed using a NASTRAN model. Under the tabulated loads, the maximum cap stress was calculated at 2400 ± 1500 psi (16.5 ± 10.3 MPa). The location is at a hole through the cap and the tabulated stress includes a stress concentration factor of three. At this stress level the bearing caps should also have near infinite life.

4.8.2.4 BEDPLATE

The bedplate was analyzed using a NASTRAN beam model. Section properties were determined for various portions of the bedplate length having nearly constant cross section. These section properties were used to define the properties of NASTRAN bar elements. Loads at the hub were applied in fifteen degree increments of blade azimuth angle. The stresses in the most highly stressed part of the bedplate are given in the following table.

BLADE AZIMUTH ANGLE, DEG	STRESS PSI	MPa	BLADE AZIMUTH ANGLE, DEG	STRESS PSI	MPa
0	5845	(40)	90	3177	(22)
15	7190	(50)	105	4271	(29)
30	7842	(54)	120	4743	(33)
45	7135	(49)	135	4066	(28)
60	5325	(37)	150	3752	(26)
75	3420	(24)	165	4464	(31)

The maximum stress occcurs at a blade angle of thirty degrees and the minimum at ninety degrees. For fatigue analysis purposes, the stress variation becomes a static stress of 5510 psi (38 MPa) and a cyclic stress of 2333 psi (16 MPa).

The most highly stressed part of the bedplate occurs where the downwind section is welded to the center section. The AISC code was used to evaluate the fatigue resistance of this weld. It was determined that this was a Category C weld subjected to Loading Condition 4 (over 2×10^6). The allowable stress range is 12,000 psi (83 MPa). The bedplate cyclic stress is well within that required for infinite life. It should be noted that this weld was subjected to radiographic inspection; it could be uprated to Category B by grinding the weld flush or to Category A by grinding flush with the grinding in the direction of the applied stress. The allowable stress range for these categories is 15,000 psi (103 MPa) and 24,000 psi (165 MPa), respectively.

4.8.2.5 YAW DRIVE SYSTEM

The original design and fatigue analysis review of the MOD-OA wind turbine yaw drive system established two basic areas of concern. These areas of concern were:

1. Fatigue life in certain components.

2. Design for adverse environments, such as high temperature, sand storms, and salt laden atmosphere.

The utilization of the two yaw drive gear boxes as preloaded counter-acting brake systems was seen as an abnormal application of this hardware which would likely result in rapid deterioration of the yaw system. The use of bronze gears to react the high external load was seen as the greatest weakness of the system. The yaw drive assembly shaft couplings were also considered to be overloaded.

A yaw brake system acting in parallel with the gear drive system was recommended to keep external loads off of the gear boxes when the yaw drive is not functioning. This recommendation was accepted and a yaw brake was added to the system to react external nacelle yaw loads. This brake system limits yaw drive loads and decreases the number of load cycles applied to the yaw drive components. The lower surfaces of the yaw drive are exposed to the outside environment which includes sand storms and rain. Providing an environmental seal between the conical support and the base of the cylindrical housing was recommended.

4.8.2.6 TOWER

The tower was modeled for NASTRAN using bar (CBAR) and rod (CROD) elements. See Section 4.5.1 for discussion of the tower model. End fixity of bars was not relieved. Ninety rod elements and 144 bar elements were required to represent the structure. To ensure infinite life, the range of stress produced in each tower member by the operating loads was computed and compared[65] with the allowable fatigue stress ranges listed in Appendix B of the AISC Code.[52]

Rated operating speed of the rotor is 40 rpm. Rotor-induced forces acting on the tower complete a cycle with each half revolution of the rotor. Therefore, less than 420 hours of rated operating time are required to generate two million loading cycles. It is necessary, then, to limit stress ranges to those values allowed for Loading Condition 4 (more than 2×10^6) of the AISC Code.

Seven allowable stress categories are listed under Loading Condition 4, with the admissible range of stress varying from 24,000 psi (165 MPa) for Category A to 6000 psi (41.4 MPa) for Category E. Selection of a particular category as the limiting design criteria is dependent upon the member type and fabrication details. For those tower elements with fillet-welded end connections, the minimum stress range of 6000 psi (41.4 MPa) is directly applicable. Most members, however, are not fillet welded and would be permitted a stress range greater than 6000 psi (41.4 MPa). It was not necessary to examine each tower element and connection detail for a differing stress range, the minimum allowable stress range of 6000 psi (41.4 MPa) was initially assumed applicable to all 234 elements of the tower model. The computer was instructed to output only those members whose computed range of stress exceeded 6000 psi (41.4 MPa). Those members so listed were then examined more closely for conformance with the Code.

The loads used in the analysis represent a relatively severe tower loading condition. This loading condition is expected to occur during operation of the

MOD-0A wind turbine near or at the maximum allowable wind velocity of 40 mph (18.0 m/s). The loads used for the NASTRAN static load subcases are shown in Table 4.8.2-5. Each subcase corresponds to one azimuthal position (fifteen degree increments of rotor angular position). Both forces and moments in the table were distributed equally to the four grid points (nodes) at the top of the tower. Both quasi-static and dynamic analyses of the tower were performed using the loads of Table 4.8.2-5. It was found that:

1. Both quasi-static and dynamic approaches give stresses which exhibit the same general profile.

2. One-percent damping has a negligible effect on the stress determined from the dynamic approach compared to that with no damping.

3. The stress determined from the quasi-static approach oscillates about a mean of 6000 psi (41.4 MPa) and has a range of about 5000 psi (34.5 MPa); that from the dynamic approach oscillates about a mean of 4300 psi (29.6 MPa) and has a range of 3000 psi (20.7 MPa).

This tends to indicate that the quasi-static approach is adequate though somewhat conservative. For that approach the minimum and maximum stresses in the rod members were -1610 and 1600 psi (-11.1 and 11.0 MPa), respectively. The minimum and maximum combined axial and bending stresses in the bar members were -8740 and 8780 psi (60.3 and 60.5 MPa), respectively. The maximum axial stress in all bar members was less than 2760 psi (19.0 MPa). Note the minimum and maximum stresses did not occur in the same member. Note also that these stresses are less than 50 percent of the static allowable stress, which is about 20,000 psi (138 MPa). The stress ranges were less than the fatigue stress allowable of 6000 psi (41.4 MPa). The stress ranges in the majority of the members of the tower were less than 3000 psi (20.7 MPa). The stress ranges were greater than 3000 psi (20.7 MPa) only in the horizontal members at the top of the tower and were mainly due to bending stresses near the end connections. It was concluded that the tower should have near infinite life.

5.0 SYSTEM TESTS AND INSTALLATION

Extensive testing was performed on the Clayton MOD-OA 200 kW WTG prior to being turned over to the utility. This testing included both in plant and site tests. The In Plant Tests presented in Section 5.1 discuss the testing completed on the drive train and nacelle equipment, rotor, and pitch change mechanism, and system checkout tests, and these tests are summarized in Table 5-1. Discussed in Section 5.2, Site Tests and Installation, are those tests which were performed on the rotor and the drive train and nacelle equipment, as well as the systems checkout tests and the installation experience, at the Clayton, New Mexico site. These site tests and the installation are summarized in Tables 5-2 and 5-3.

TABLE 5-1: IN PLANT TESTS OF CLAYTON MOD-OA 200 kW WTG

DRIVE TRAIN AND NACELLE EQUIPMENT (Without Blades and Hub; Sec. 5.1.1)
- Rotational Checkout
- Dynamic Balancing of Drive Train
- Drive Train Run-In at Various Power Levels

ROTOR (Without Blades; Sec. 5.1.2)
- Strain Gage Calibrations
- Balancing of Hub Assembly (Static and Dynamic)

PITCH CHANGE MECHANISM (Sec. 5.1.3)
- Static (Drive Train Not Operating)
- Dynamic (Drive Train Operating)

SYSTEM CHECKOUT (Sec. 5.1.4)
- Yaw Drive System
- Sensor Installation and Wiring Verification
- Microprocessor (Performed at MOD-0)

TABLE 5-2: SITE TESTS OF CLAYTON MOD-OA 200 kW WTG

ROTOR (Sec. 5.2.1)
- Instrumentation Checkout
- Pitch Change Mechanism

SYSTEMS CHECKOUT (Sec. 5.2.2)
- Yaw Drive System
- Safety Shutdown System
- Pitch Control System
- Manual and Automatic Shutdown

DRIVE TRAIN AND NACELLE EQUIPMENT (Sec. 5.2.3)
- Rotating Tests
- Dynamic Balancing
- Manual and Automatic Startup

The arrangment of all of the components located within the nacelle for the MOD-OA WTG was shown previously in Figure 2.3-1. This sketch depicts the attachment of the rotor blades and pitch actuator to the hub; the attachment of

TABLE 5-3: INSTALLATION OF CLAYTON MOD-OA 200 kW WTG*

- Site Preparation (and Sec. 5.2)
- Pouring of Foundations
- Tower Erection
- Reassembly of Drive Train to Support Cone and Service Stand
- Blade Installation (and Sec. 5.2.1)
- Control Building and Auxiliary Equipment
- Equipment and Personnel Hoist
- Lift to Top of Tower
- Complete Electrical Terminations and Utility Connection (and Sec. 5.2.2)
- First Rotation, Dedication, and Turn-Over to Utility for Operation

* Sec. 5.2.4 except where noted.

the rotor assembly to the low speed shaft and speed increaser; the location of the fluid coupling and the disk (rotor) brake; the high speed shaft, bearings, V-belts, and generator; the hydraulic power supply for the pitch change mechanism; and the bedplate, yaw drive system, and yaw brake. This figure provides an introduction to some of the mechanical and electrical components and systems which were evaluated during the in plant and site tests.

Shown in Figure 5-1 is a flow chart for the assembly of the Clayton WTG at the NASA Lewis Research Center. The in plant tests of Table 5-1 were performed during various phases of this assembly. Shown in Figure 5-2 is a flow chart for the assembly of the MOD-OA at Clayton, NM. The site tests and installation summarized in Tables 5-2 and 5-3 and presented in Section 5.2 were completed during various phases of this assembly.

5.1 IN PLANT TESTS

Several test series were performed at the NASA LeRC during various stages of the assembly and checkout of the components and systems for the MOD-OA WTG (see Table 5-1 and Figure 5-1). These in plant tests were designed to verify that a) all parts and components were manufactured according to specifications and correctly assembled and aligned, and b) all electrical, instrumentation, and control system components were installed and connected in accordance with the applicable drawings and specifications. Prior to the performance of the in plant tests, tests were conducted on some of the components for the MOD-OA WTG at the manufacturer's facility. For example, a no-load run-in test of the speed increaser was performed by the manufacturer: Horsburgh & Scott Company.

A product assurance plan for the MOD-OA wind turbine was implemented by the NASA LeRC to establish the reliability and quality assurance aspects of the WTG. This plan delineated the project controls on design and reliability, the configuration control, procured article control, and the in-house controls for inspection, testing, failure reporting, project logs, and calibration. The reliability and quality assurance tasks included a complete review of the engineering drawings, purchase requests, and inspection reports for all of the

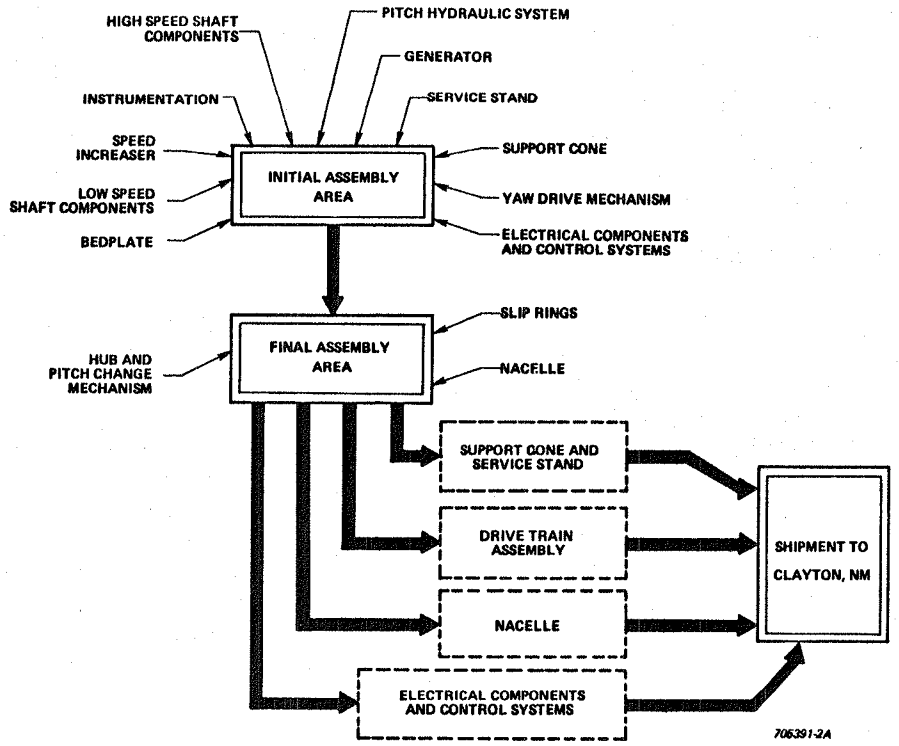


Figure 5-1. Flow Chart for Assembly of MOD-OA WTG at NASA Lewis Research Center

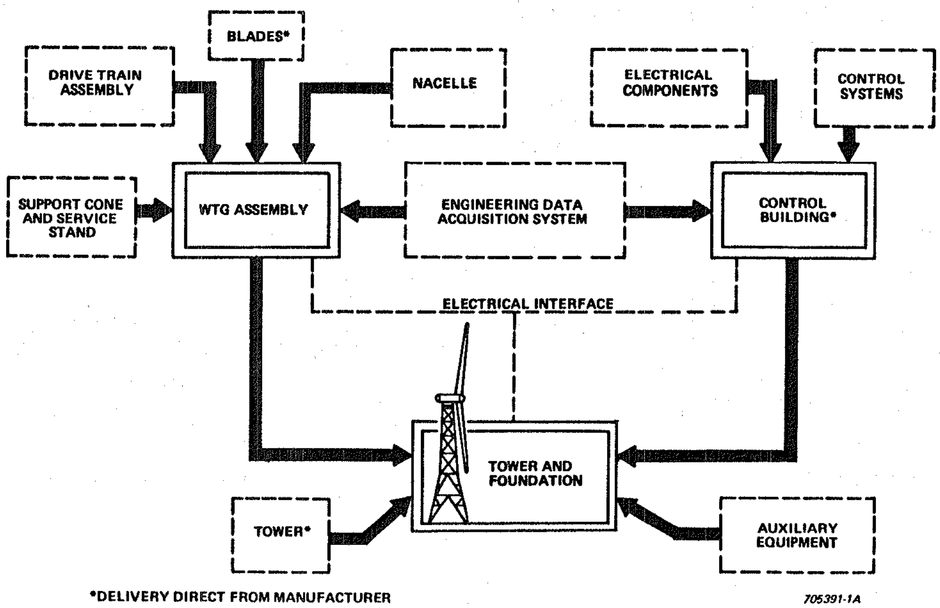


Figure 5-2. Flow Chart for Assembly of MOD-OA WTG at Clayton, N.M.

critical components. Also, sample reviews were performed on the drawings, purchase requests, and inspection reports for the non-critical components. The product assurance plan was followed during the design, procurement, assembly, and testing of the components for the drive train and nacelle equipment, rotor, pitch change mechanism, yaw drive mechanism, control systems, and other systems and components of the WTG.

5.1.1 DRIVE TRAIN AND NACELLE EQUIPMENT

The assembly and acceptance testing of the Clayton MOD-OA WTG was accomplished in three phases. The first phase involved the assembly and testing of the drive train without the blades, hub, pitch change mechanism, and pitch hydraulic system. Thus, the assembly of the drive train consisted of the following components: low speed shaft, bearings and coupling; speed increaser; high speed shaft, rotor brake, bearings, couplings, fluid coupling, and belt drive; and the generator; as these components were attached to the bedplate. Shown in Figure 5.1.1-1 is a sketch of the setup for the in plant testing of the drive train assembly. This test setup included the use of a dynamometer and a speed reducer to simulate the torque at the rotor hub, as these components were connected to the low speed shaft and utilized to power the drive train assembly.

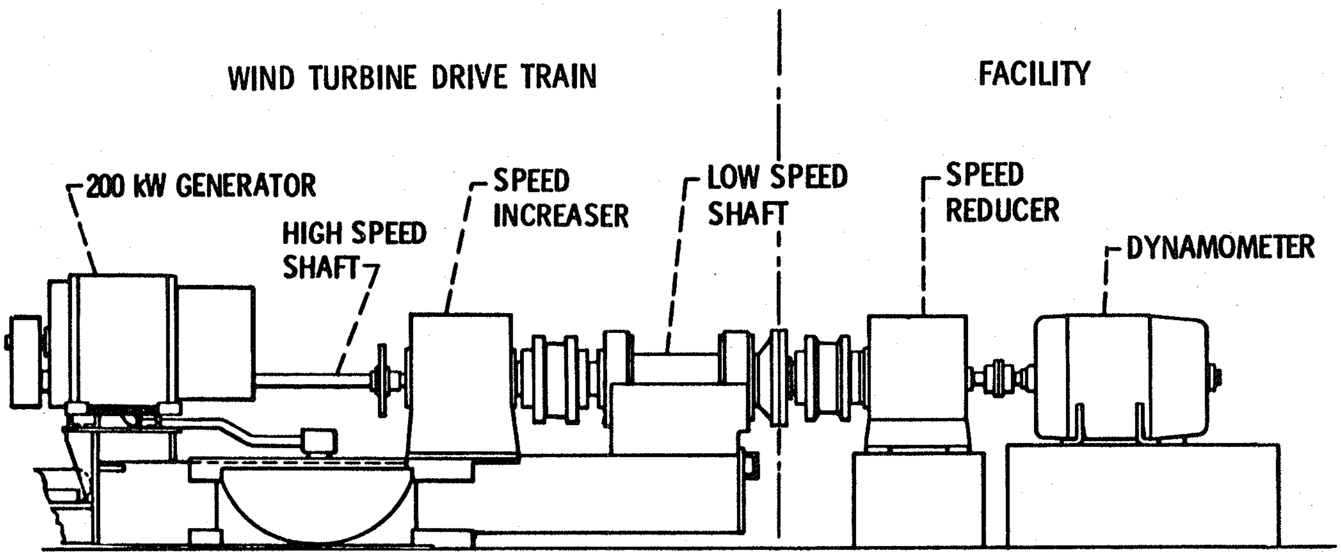


Figure 5.1.1-1. Sketch of Setup for In Plant Testing of the Drive Train Assembly

ROTATIONAL CHECKOUT TESTS

Before the dynamic balancing and the Phase I testing of the drive train assembly could be performed, rotational checkout tests were completed on three configurations (portions) of the drive train assembly as various components were added to the bedplate. The purpose of conducting these checkout tests was to detect early in the assembly schedule any misalignments or defects in the rotating components before the assembled wind turbine was subjected to the Phase I testing. Initially, the low speed shaft and speed increaser were mounted on the bedplate and connected to the dynamometer and speed reducer at a test facility in the Engine Research Building of the NASA LeRC. Shown in Figure 4.2.1-2 is a photograph of the low speed shaft, bearings, coupling, and speed increaser which were tested during this first rotational checkout test. Testing was performed at three different rotational speeds for the dynamometer: 600, 1200, and 1800 rpm, and various types of data were collected.

The second series of rotational checks was performed after the high speed shaft and its associated components were connected and aligned to the output shaft of the speed increaser. The third series of rotational checkout tests was completed after the belt drive and generator were assembled to the drive train. A photograph of the high speed shaft, high speed bearings, belt drive, and generator was shown previously in Figure 4.2.3-3. This photograph depicts the final series of components which were evaluated during the rotational checkout tests. The testing performed during the second and third rotational checks was similar to that performed for the first, except that additional instrumentation was monitored and other parameters were investigated. Presented in Table 8.1-2 are the locations and functions of the various sensors located on the drive train assembly, some of which were monitored and recorded during these rotational checkout tests.

Results of the test data taken during these rotational checks showed that all temperatures, except the upwind high speed shaft pillow block bearing temperature (sensor number 06T252 as listed in Table 8.1-2), were well within their acceptable ranges. The acceptable range for the pillow block bearing temperature was up to 200°F (93°C) and the red line value was 300°F (149°C). The maximum temperature measured was 218°F (103°C). As a result of this testing, an improvement was incorporated into the design in which these bearings packed with grease were changed to bearings in oil. Subsequent testing of the high speed shaft bearing assembly confirmed the lowering of these temperatures.

DYNAMIC BALANCING OF DRIVE TRAIN ASSEMBLY

Dynamic balancing of the drive train assembly was performed with the high speed shaft rotating at 1800 rpm. This balancing was done both prior to and after the installation of the fluid coupling and included testing with the generator loaded to 150 kW. After the dynamic balancing operations, accelerometer and/or vibration amplitude readings were monitored in the vertical and horizontal orientations on the low speed shaft bearings and on the two pillow block bearings on the high speed shaft, as well as at other locations in the drive train assembly. The final peak-to-peak vibration amplitude data indicated that all locations were found to be acceptable.

DRIVE TRAIN RUN-IN TESTS

With the wind turbine components and test support equipment arranged in the Phase I assembly configuration as shown in Figure 5.1.1-1, a series of drive train run-in tests at various generator power output levels was performed. The MOD-0A wind turbine components mounted on the bedplate for this Phase I testing, as well as the dynamometer and speed reducer of the test facility, (comparable to that depicted in the sketch of Figure 5.1.1-1) are shown in Figure 5.1.1-2. The tests of the drive train assembly were accomplished by operating the dynamometer at a constant speed of 1800 rpm and varying the resistance load bank to obtain the following generator power output levels: no load, 50-60 kW, 90-100 kW, and 140-150 kW. The drive train was tested for an eight hour period at each of these power levels.

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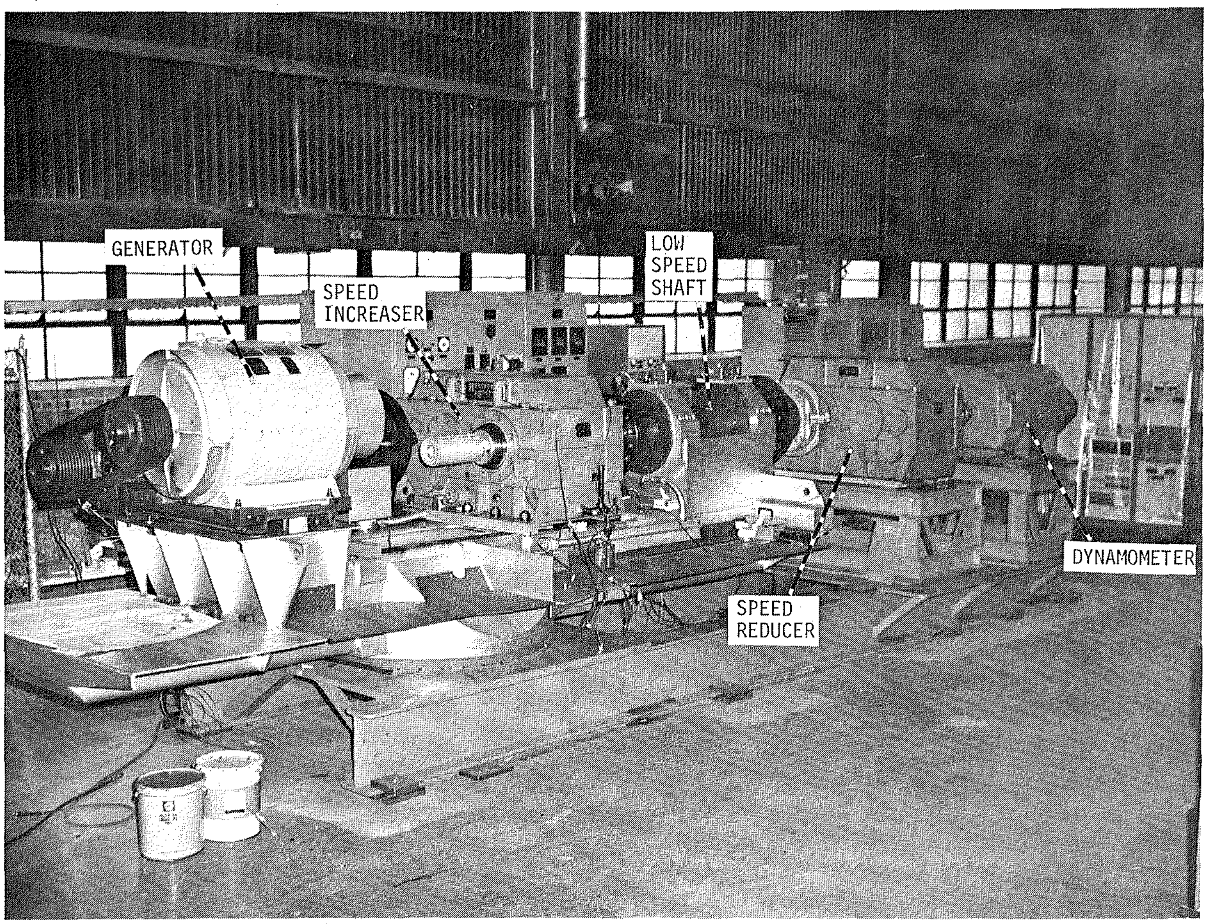

Figure 5.1.1-2. Photograph of In Plant Test Setup for Drive Train Assembly

The instrumentation monitored and recorded during the drive train testing included the accelerometers (located on the front and rear low speed shaft bearings and on the upwind high speed shaft pillow block bearing), temperatures (front and rear low speed shaft bearings, speed increaser oil, pillow block bearing, generator winding, and the low speed and high speed bearings of the speed increaser), rotational speeds (generator rpm, low speed shaft rpm, and generator output frequency), and generator output parameters as listed in Table 8.1-5 (generator power output in kW, voltages and currents for each of the three phases, field current, and generator output VARS). For each of these instrumentation sensors, both normal and maximum operating ranges were specified. During this testing, the oil level in the speed increaser was lowered and the type of oil was changed from AGMA No. 4 to a synthetic. These changes resulted in a lower operating temperature. Shown in Figure 5.1.1-3 are curves of the temperature of the oil in the speed increaser as a function of time during two drive train tests at 100 kW. The temperatures for the second test were lower than those for the first because the oil level had been lowered and because of a lower starting temperature. These temperature profiles are representative of other temperatures recorded during the tests.

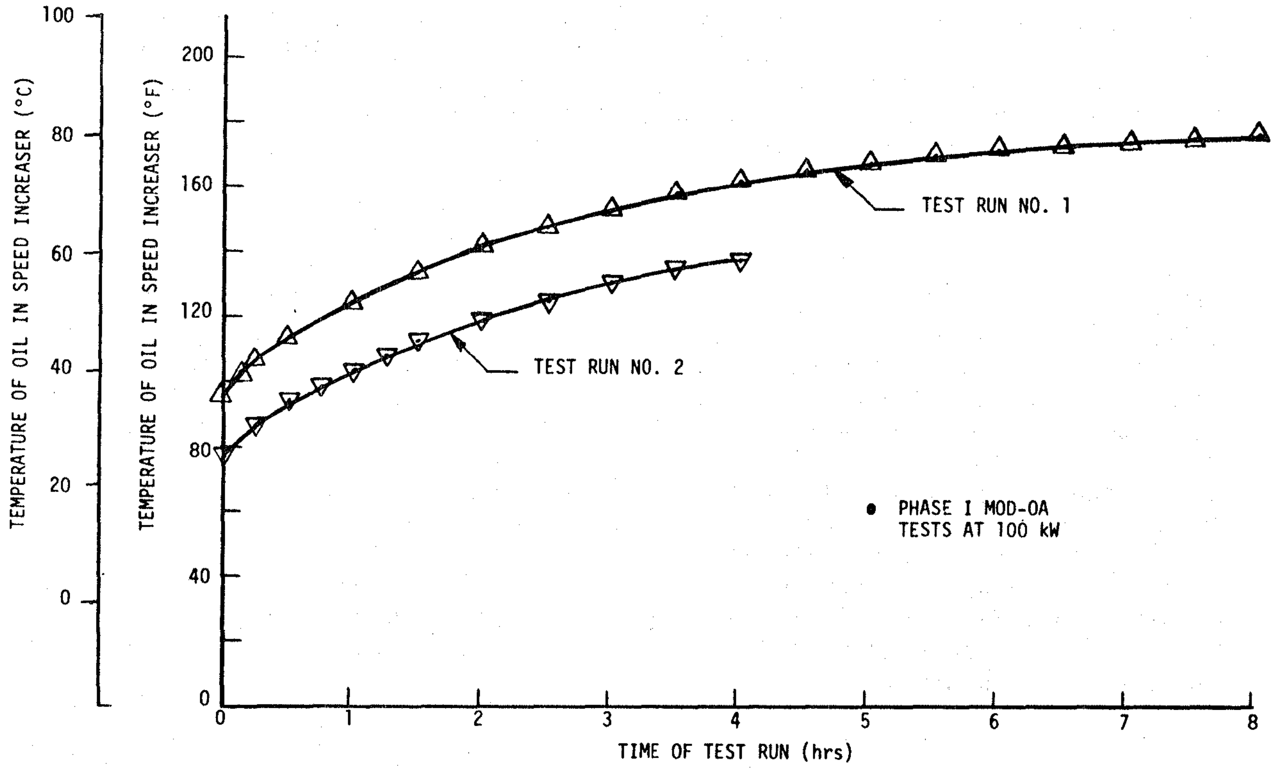

Figure 5.1.1-3. Temperature of Oil in Speed Increaser as a Function of Time for Drive Train Tests

HYDRAULIC SYSTEM TESTS

Tests were also performed on the hydraulic system which supplies high pressure fluid to the pitch change mechanism.

5.1.2 ROTOR

The in plant tests on part of the rotor assembly (i.e., without the blades) for the MOD-OA WTG consisted of strain gage calibration tests and static and dynamic balancing of the hub assembly.

STRAIN GAGE CALIBRATION TESTS

The strain gage calibration testing was performed at the NASA LeRC Fabrication Shop (Building 50). Strain gages were installed on the low speed shaft to measure bending loads and torque during operation of the WTG. Strain gages were also installed on the bedplate to measure bending loads during operation. In order to calibrate these gages, the bedplate was mounted on the support cone/service stand. The service stand was attached to a concrete foundation and this attachment was sufficient to withstand the loads applied during testing. The calibration of the strain gages yielded a millivolt output per volt supplied to the strain gage bridge per ft.-lb. of load. Additional reasons for this testing were: a) to determine the "crosstalk" and b) to provide input to the computer in the mobile data system, resulting in engineerig data outputs. The strain gage calibration tests were performed in three steps: bending loads, shaft torque, and combined loads tests.

The six strain gages on the low speed shaft which required calibration are listed in Table 8.1-1. During the bending and combined loads tests, calibration of the following strain gages was completed: 04S174, 04S176, 04S178, and 04S180. Also, two additional gages: 08S358 and 08S360 (see Table 8.1-3) located on the top and bottom of the bedplate were calibrated during this testing. During the shaft torque and combined loads tests, two strain gages: 04E170 and 04E172 (see Table 8.1-1) were calibrated. In addition, the bedplate strain gage data were monitored during these shaft torque tests.

All of the strain gage calibration tests were performed with the use of a "spider" assembly type loading fixture which was attached to the rotor end of the low speed shaft (in place of the hub). Also used during the bending, torque, and combined loads applications were load cells and recorders. Shown in Figure 5.1.2-1A and -1B are photographs of the loading fixture and test setup for the strain gage calibration testing. Prior to the testing, the load cells were calibrated.

The strain gage calibration tests permitted a checkout of the proper hookup of the various gages. The initial data derived showed that a collar added to the low speed shaft was sharing the load and affecting the readings from the strain gages located under the collar. Therefore, new gages were added to the low speed shaft at a different location. Also, strain gage checkout tests were performed at the Clayton, NM site after the blades were attached to the hub of the rotor assembly.

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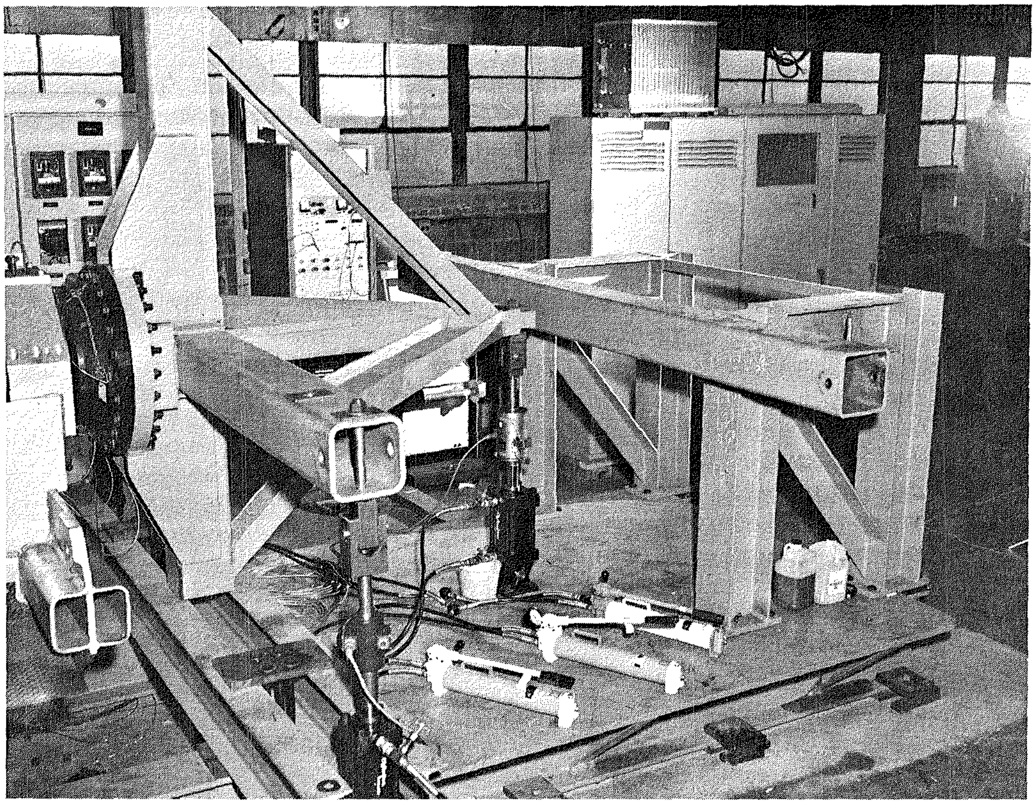

Figure 5.1.2-1A. Photograph of Loading Fixture and Test Setup Used During Strain Gage Calibrations (Side View)

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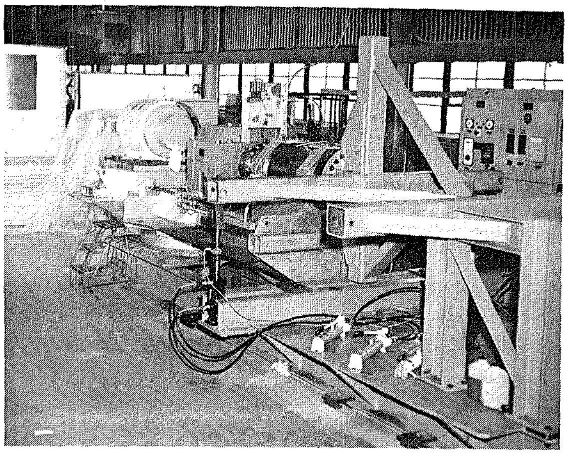

Figure 5.1.2-1B. Photograph of Loading Fixture and Test Setup Used During Strain Gage Calibrations (Looking Upwind)

The bending loads calibration tests were performed by applying a bending moment to the low speed shaft as a force couple to the loading fixture. This bending moment on the shaft was applied in increments of 20% of the maximum to a maximum moment of 100,000 ft.-lbs. (136,000 Nm). Removal of the load was in increments of 20% of the maximum load. This calibration was repeated with the load direction reversed. These two tests were repeated with the load fixture advanced 45° and 90° relative to the shaft. This resulted in six applications of the loading: two conditions (plus and minus load) for each of the three positions of the loading fixture relative to the shaft. During the bending loads calibrations, the yaw brake was engaged by applying 1000 psig (6.9 MPa) gaseous nitrogen (for testing purposes) to the caliper brakes. Shown in Figure 5.1.2-2 are the strain gage calibration test results for Sensor No. 04S174 for the bending moment test at 0°, in which the applied bending moment is plotted as a function of millivolts output from the strain gage.

In order to calibrate the strain gages used for monitoring the torque loading on the low speed shaft during WTG operation, a torsional force couple was applied to the loading fixture mounted on the shaft. During these calibrations, the disk (rotor) brake located downwind of the speed increaser on an extension of the high speed shaft was engaged by applying 80 psig (0.55 MPa) gaseous nitrogen to the brake. Also, the yaw brake was engaged by applying 1000 psig (6.9 MPa) gaseous nitrogen to the calipers of the yaw brake system. Torque was applied in increments of 20% to a maximum value of 50,000 ft.-lbs. (68,000 Nm). These tests were repeated with the load direction reversed. Shown in Figure 5.1.2-3 are the strain gage calibration results for torque loading on the low speed shaft, in which the applied torque is plotted as a function of the strain gage output voltage for sensors 04E170 and 04E172.

Combined bending moment and torque tests were performed using the loading fixture mounted on the low speed shaft. The combined loads were applied in the following manner: bending loads in 20% increments up to 100,000 ft.-lbs. (136,000 Nm) and set at 100,000 ft.-lbs. (136,000 Nm), then a torque load was applied at 25,000 ft.-lbs. (34,000 Nm) and 50,000 ft.-lbs. (68,000 Nm). The loads were removed in the reverse order, i.e., the torque load was removed and then the bending moment. This combined loading sequence was performed with the load fixture attached at three angular positions: 0°, 45°, and 90°, relative to the locater mark on the low speed shaft. Both the yaw brake and disk brake, as discussed above, were engaged during this combined loads calibration test.

The results from the above strain gage calibration tests were derived by direct connection to each of the gages at their various locations. During actual operation of the MOD-OA WTG, the output from the strain gages located on the low speed shaft (as well as other instrumentation signals) are transmitted to the remote multiplexer unit mounted on the hub, then along the inside of the hollow low speed shaft, and finally to the rotor slip ring. A photograph of the rotor slip ring was shown previously in Figure 4.6.4-1.

BALANCING OF HUB ASSEMBLY

Prior to the performance of the static and dynamic balancing of the hub assembly (Test No. 1 of Phase II), the strain gage calibration loading fixture was removed from the low speed shaft. Then, the hub of the rotor assembly

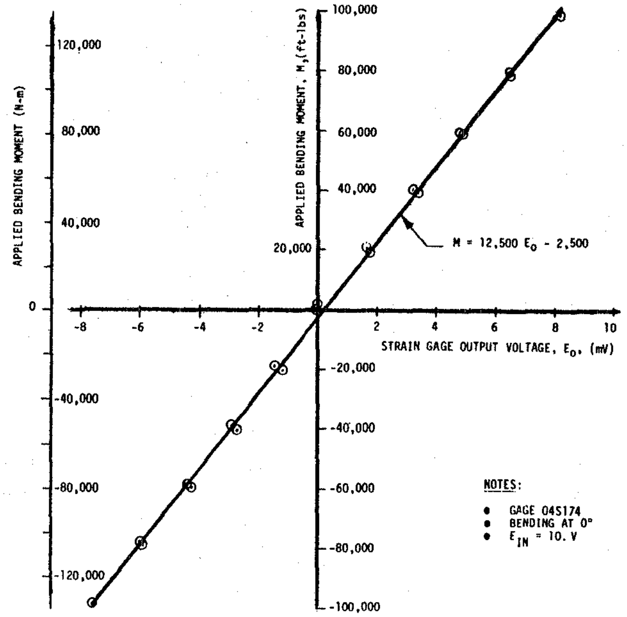

Figure 5.1.2-2. Strain Gage Calibration Results for Bending Moments on the Low Speed Shaft

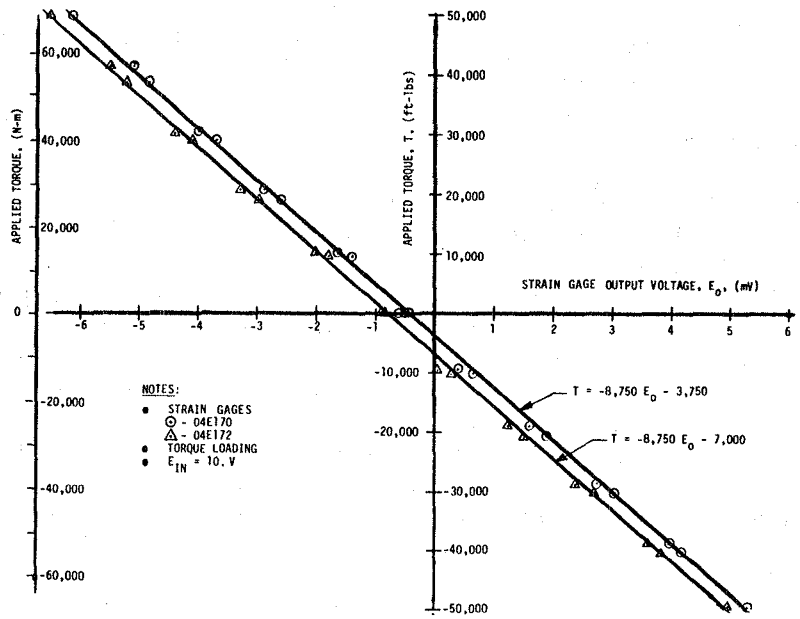

Figure 5.1.2-3. Strain Gage Calibration Results for Torque Loading on the Low Speed Shaft

(without the blades) was attached to the low speed shaft. All of the components of the pitch change mechanism and the pitch hydraulic system were installed on the hub in preparation for the hub balancing operations.

The MOD-OA WTG components and test support equipment were arranged in accordance with the Phase II test configuration. The Phase II tests consisted of both static tests (with the drive train not operating) and dynamic tests (drive train operating with the low speed shaft and hub assembly rotating at 40 rpm). The drive train was operated by using the generator as a synchronous motor powered from an external power supply. During the tests when the drive train was being operated, most of the instrumentation discussed above in Section 5.1.1, i.e., various accelerometers, temperatures, rotational speeds, etc., were continuously monitored and recorded to ensure that the normal operating ranges or design limit conditions were not exceeded.

The balancing operations on the hub assembly consisted of both static and rotating (dynamic) tests. This hub assembly was complete with the multiplexer and pitch change actuator units installed, except that the blades were not added to the assembly. With the coupling on the low speed shaft disconnected, static balancing was accomplished by installing steel weights, as required, to the exterior surface of the hub. The assembly was considered balanced when it no longer rotated from any given position due to its own inertia. During this balancing operation, extreme care was taken to prevent damage to the wiring and hydraulic lines located inside the low speed shaft.

Dynamic balancing of the hub assembly was accomplished with the coupling on the low speed shaft reconnected and the hub rotating at 40 rpm. Balance weights were added or adjusted as required. The hub assembly was considered balanced when the acceleration readings on the low speed shaft support bearings (front and rear) were no greater than those recorded during the Phase I dynamic balancing tests. As a result of the static and rotating tests, satisfactory balancing of the hub assembly was completed.

5.1.3 PITCH CHANGE MECHANISM

Testing of the pitch change mechanism and its control system was completed as part of the Phase II test sequence. The purpose of these tests was to verify the performance of the pitch change mechanism and pitch control system both statically (drive train not operating) and dynamically. The wind turbine components and pitch control system were installed in accordance with the Phase II test configuration. All systems, including the pneumatic spring fail-safe system were connected and operable. Prior to this testing, the hub, pitch change mechanism, pitch hydraulic system, support cone, and yaw drive assembly were added to the drive train components and the WTG was mounted on the service stand. Shown in Figure 5.1.3-1 is a sketch of the WTG assembly without the blades, as it was evaluated during the in plant Phase II and Phase III acceptance testing.

Shown previously in Figure 2.6-1 was a simplified schematic of the pitch hydraulic system and its interface with the pitch change mechanism. The pitch hydraulic system is located in the upwind end of the nacelle and its fluid is pumped to the pitch change mechanism through a rotating hydraulic union coaxial

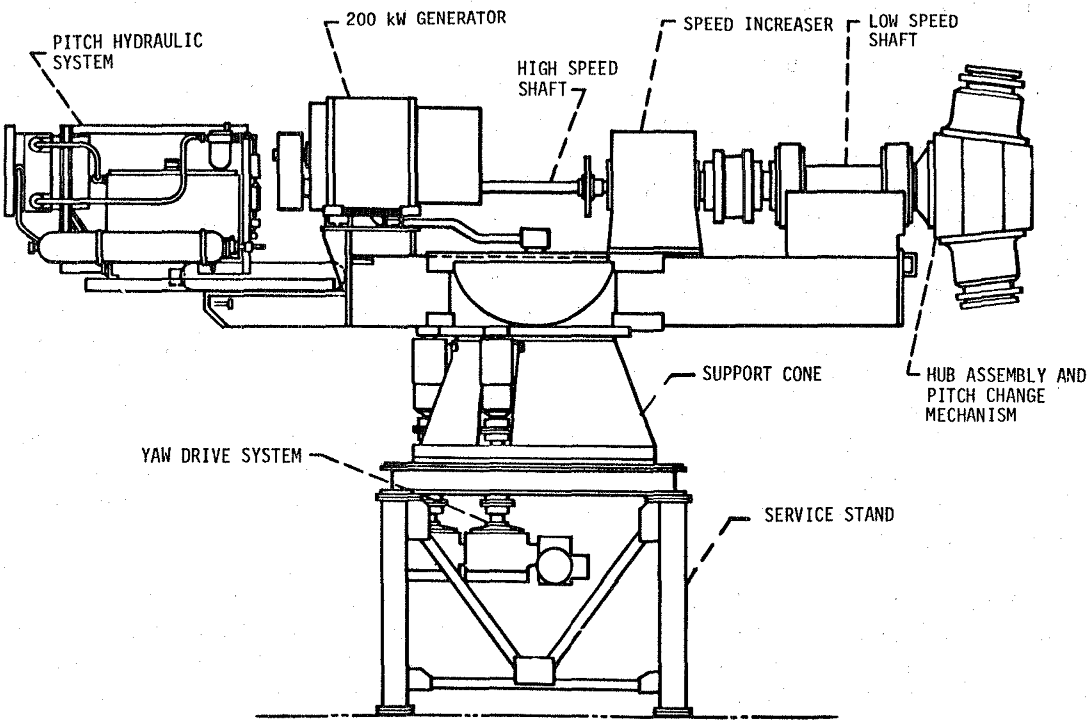

Figure 5.1.3-1. Sketch of In Plant Test Setup for Phase II and III Acceptance Testing

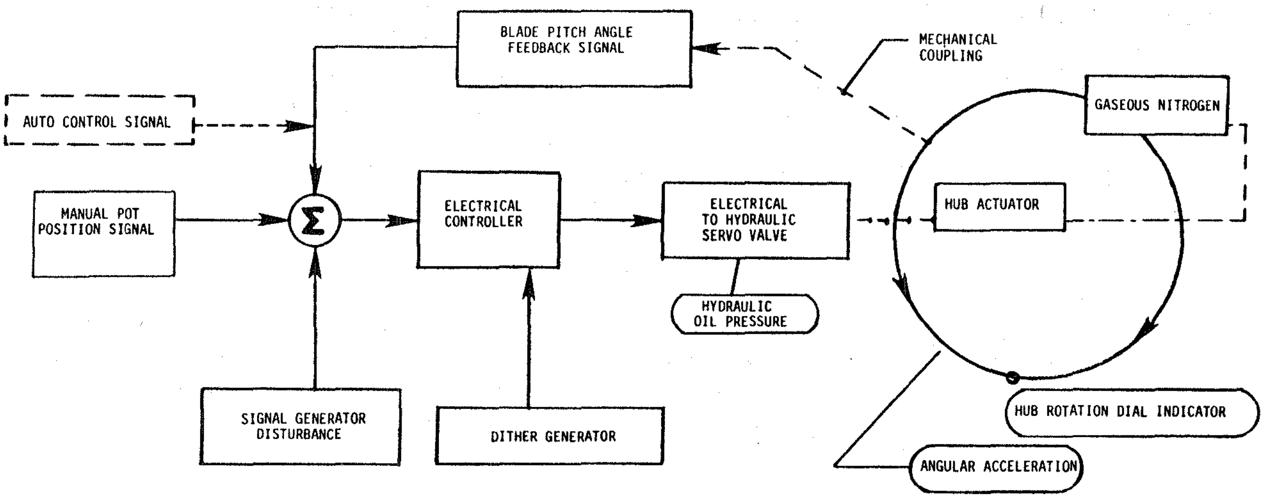

Figure 5.1.3-2. Block Diagram of Pitch Control System for In Plant Tests

with the low speed shaft. A photograph of this rotating hydraulic union was shown in Figure 4.1.3-4. Also, presented previously in Figure 4.1.3-2 was a photograph of the pitch change mechanism mounted on the rotor hub.

The MOD-OA WTG is brought up to speed and maintained at a given output power by varying the pitch angle of the blades. Shown in Figure 5.1.3-2 is a block diagram of the blade pitch control system that accomplishes this task. Included in this figure are the main components of the control system and some of the system measurements. An electrical signal controls the hydraulic oil flow to the pitch actuators. These hydraulic actuators rotate the blades through a gear drive, as shown previously in Figure 4.1.3-3. A position transducer measures the blade pitch angle and provides a feedback signal to the electrical controller. A summing circuit compares this feedback signal to either a manual setpoint or an automatically controlled signal. The automatic signal requires logic involving the microprocessor. Since the microprocessor was not available for these tests, the automatic portion of the controller was not evaluated at that time. To test the control system, ramped, square wave, and sine wave signals were inserted at the summing circuit. In the event of a loss of hydraulic pressure, a gaseous nitrogen actuator drives the blades to a feathered condition.

Tests were performed in Building 50 at the NASA LeRC on the pitch change mechanism and its control system to evaluate performance characteristics. Both static testing (with the drive train not operating and the rotor blade simulators* installed) and dynamic testing (without the blade simulators* and with the drive train operating at 40 rpm, using the generator as a motor) were conducted. The main objectives of these tests were to determine the sensitivity, linearity, resolution, hysteresis, stability, rates of travel, dither, frequency response, and accelerations of the pitch change mechanism and pitch control system for different disturbances.

STATIC TESTS

Static testing of the pitch change mechanism and pitch control system included manual pot calibration, resolution, slow pitch rate, maximum speed, fail-safe mechanism, frequency response, acceleration, and deceleration tests. The dynamic testing of the pitch change mechanism and its control system consisted of slow pitch rate, fail-safe speed control, and maximum speed tests. Extensive instrumentation was monitored and recorded and test results were derived to evaluate performance during each of the above static and dynamic tests. Since several different tests were performed, the results from these tests have been summarized, and only representative sketches, curves, or photographs and condensed test descriptions have been included.

As part of the static tests on the pitch change mechanism, a pitch change inertia test was performed. A dummy weight, which simulated the pitch change inertia of the blade, was mounted on each blade spindle where the blades are normally attached. Shown in Figure 5.1.3-3 is a photograph of these blade

* Dummy weights which simulate the pitch change inertia of the blades

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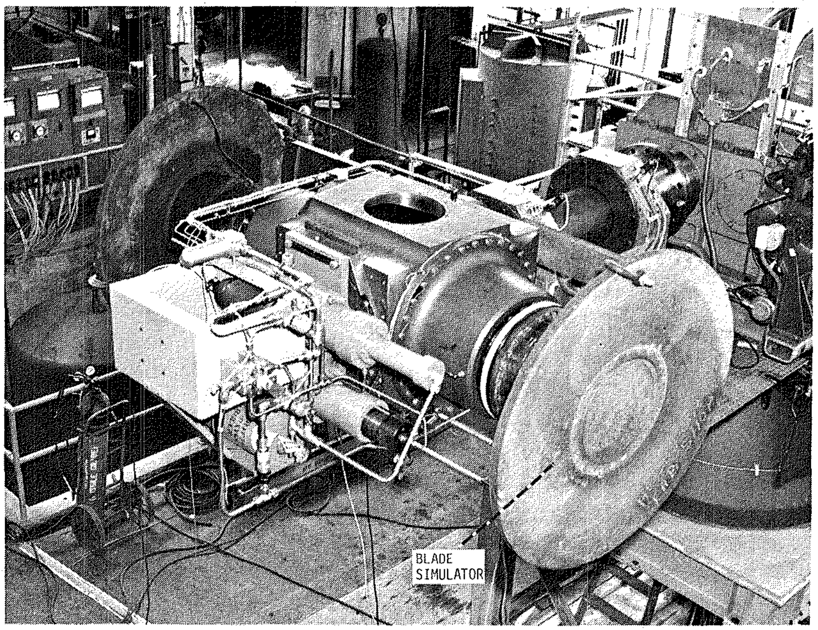

Figure 5.1.3-3. Blade Simulators Attached to Hub Assembly for Static In Plant Testing of Pitch Change Mechanism

simulators attached to the hub assembly, as well as some of the components of the pitch change mechanism and pitch hydraulic system. The complete pitch hydraulic system, including the pump, control valves, rotating hydraulic union, and hydraulic actuators were operated and evaluated during these tests. All static tests of the pitch control system and pitch change mechanism were completed with the blade simulators installed on the hub. The pitch hydraulic system was operating at its normal system pressure of 1500 psig (10.3 MPa) and the pneumatic spring pressure was set at its normal operating pressure of 1800 psig (12.4 MPa).

The resolution of the pitch change controller was determined during the static tests by using a dial indicator mounted on the outer edge of the blade simulator. With the system on "manual", the actuator was driven to the 50% stroke position and the dial indicator set at zero. Then the actuator was moved in one direction in the smallest possible steps. Potentiometer settings and dial indicator readings were tabulated for five steps in one direction, the direction was reversed, and these data were recorded for the five steps back. The drift was determined by setting the "manual" potentiometer to 50% and holding for approximately 20 minutes while tabulating the dial indicator readings every 15 seconds.

In performing the slow pitch rate test, the pitch change controller was commanded to drive the pitch change actuator at a rate of 0.2°/sec over its full stroke (97° of blade pitch angle) in both directions. The command signal and actuator position feedback signal were recorded during this test. The test was repeated while stroking between the limits of 25% and 75% of full stroke.

Using a function generator to drive the input, a frequency response test from 0.05 Hz to 5.0 Hz, with an input amplitude of ± 0.5° of actuator rotation, was completed. The input command signal and the actuator feedback signal were recorded during this test.

For the acceleration and deceleration testing, an accelerometer was mounted on one of the blade simulators. The data from this accelerometer was converted to an angular acceleration of the blade simulators. The maximum acceleration and deceleration rates that can be imposed by the pitch control system and by activating the fail-safe solenoids were determined from tests performed at 5%, 50%, and 95% of full stroke. In performing some of these tests, step inputs were applied to the actuator. Also, the maximum deceleration rate that the servo unit can impose on the system, when the servo valve spool is centered, was evaluated.

For the maximum speed test, the maximum stroke speed of the pitch change servo system was evaluated. These tests were performed with the pitch actuator moving in each direction and the time required for full stroke (97°) was recorded. During the fail-safe speed control calibration tests, the full stroke fail-safe time in 10% step settings of the fail-safe flow regulating valve was tabulated. This test was performed while operating the hydraulic system at a normal pressure of 1500 psig (10.3 MPa) plus a normal pneumatic spring pressure of 1800 psig (12.4 MPa), and again while driving the system with the pneumatic spring pressure alone.

DYNAMIC TESTS

The dynamic tests performed on the pitch change mechanism and pitch control system were a slow pitch rate, a fail-safe speed control, and maximum speed tests. These tests were conducted with the blade simulators removed, the drive train operating at 40 rpm, and the pitch change hydraulic and pneumatic spring pressures set at their normal operating pressures. The dynamic slow pitch rate test procedure was identical to that for the static slow pitch rate test. The fail-safe speed control test was performed with the fail-safe flow regulating valve set and locked in the position determined from the static tests on the fail-safe speed control calibration. The full-stroke time for a 97° pitch change was measured and tabulated with the pitch actuator moving in each direction. The procedure for the dynamic maximum speed test was identical to the static test procedure for maximum speed.

TEST RESULTS

Shown in Figure 5.1.3-4 are the results derived during the manual pot calibration (static) tests of the pitch controller, in which the hub rotation in degrees is plotted as a function of the manual pot division. Additional results from the static and dynamic performance tests conducted on the pitch control system and pitch change mechanism were as follows:

- Manual Pot Control Sensitivity - 0.0035 blade pitch angle volts/division.
- Blade Pitch Angle Voltage Sensitivity - 27.9 hub degrees/V (0.487 hub rad/V)

- Nonlinearity - less than 0.1 degrees (0.0017 rad)
- Hysteresis - less than 0.013 hub degrees (0.00023 rad)
- Resolution - fraction of manual pot divisions (less than pot readability)
- Null Repeatability - less than 0.0024 hub degrees (0.000042 rad)
- Stability (Drift) - less than 0.003 hub degrees (0.000053 rad) per 22 minutes
- Smoothness - feedback signal followed input signal (without lagging or any discontinuity from feather to power to feather position)
- Rates of Travel (Rates Were Same for Static and Dynamic Operation):
  - feather to power = 7.3 hub degrees/sec (0.127 rad/s)
  - power to feather = 8.8 hub degrees/sec (0.154 rad/s)
  - full travel (97°) (1.69 rad) fail-safe feather time = 20.4 sec (regulating valve setting of 3.5)
- Frequency Response:
  - 3 db down at 5.3 Hz
  - 45 degrees (0.785 rad) lag at 2.2 Hz
- Maximum Acceleration = 19 rad/s^2
- Dither to Servo Valve was found to be sensitive to control position. For example:
  - manual pot = 50 divisions, dither = 275 Hz at 0.2 p-p
  - manual pot = 900 divisions, dither = 725 Hz at 0.62 p-p

The results obtained were deemed satisfactory and similar to the MOD-0 (100 kW) wind turbine performance.

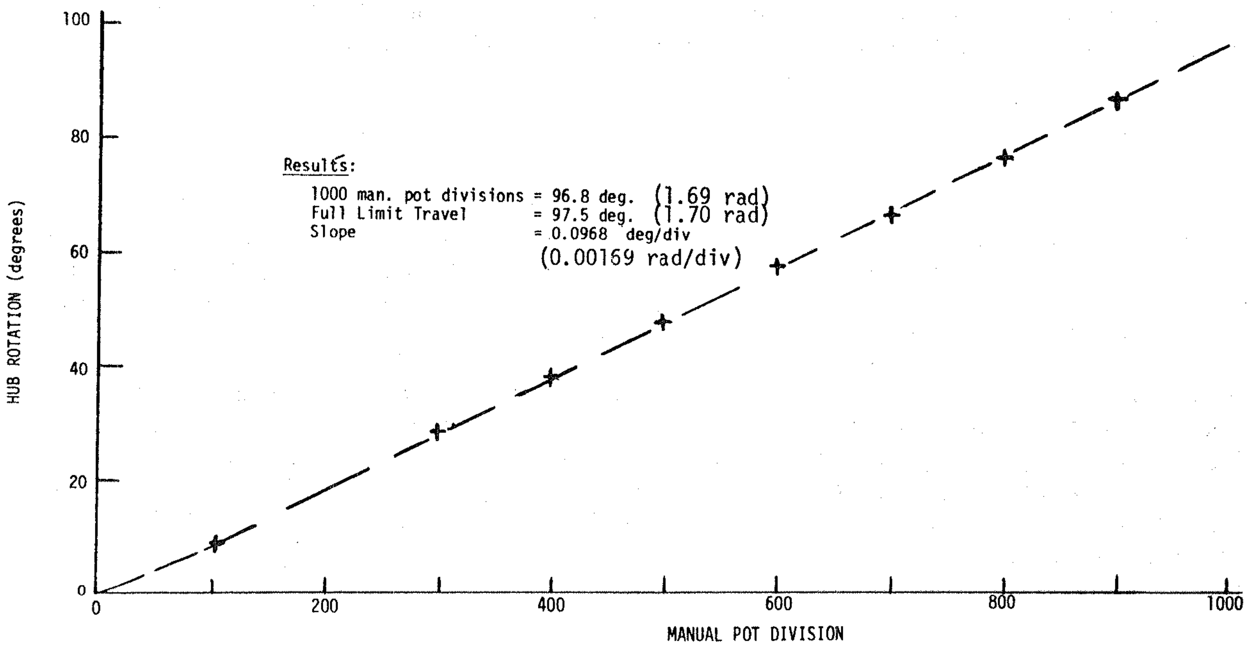

Figure 5.1.3-4. Manual Pot Calibration Results for Pitch Controller

5.1.4 SYSTEM CHECKOUT

The checkout of the MOD-OA WTG system was performed during the Phase III tests. These tests consisted of Test No. 1, a Yaw Drive System Test; and Test No. 2, a Sensor Installation and Wiring Verification Test. Also, complete checkout tests of the microprocessor were performed. Shown previously in Figure 5.1.3-1 was a sketch of the in plant test setup for the Phase II and Phase III acceptance testing. For these in plant tests, the support cone and mounting frame (which house the yaw drive system and yaw brake), as well as the turntable bearing, were assembled onto the service stand (See Figure 5.1.3-1). The bedplate and all of the components and systems contained within the nacelle, including the hub (without the blades), were assembled and the bedplate was attached to the turntable bearing. All electrical, mechanical, hydraulic, and data acquisition system components were connected, including the low speed shaft slip ring. The switchgear and most of the control systems were connected and operational.

Shown in Figure 5.1.4-1 is a photograph of the service stand, mounting frame, support cone, and part of the yaw drive system and yaw brake, as well as the control rack. Several other photographs of the various components and systems during the interim assembly of the MOD-OA WTG have been included elsewhere in this report. Shown previously in Figures 2.7-2 and 4.4-3 were detailed photographs of the yaw brake system. A photograph of the hub and pitch change assembly after these components were connected to the low speed shaft was presented in Figure 4.1.2-2. Shown in Figure 8.2-1 was a photograph of the remote multiplexer unit (RMU #2) mounted on the bedplate. Two other RMUs were used in the engineering data acquisition system, one located on the hub and the other in the control building. Presented previously in Figure 4.3-1 was a photograph of the bedplate, drive train components, hub assembly, hydraulic power supply, support cone, mounting frame, and yaw drive system.

YAW DRIVE SYSTEM TESTS

Shown in Figure 5.1.4-2 is a photograph of the MOD-OA WTG assembly prior to the Phase III in plant system checkout tests. The first tests were performed on the yaw drive system after the WTG components and control systems were arranged and connected in the Phase III test configuration.

This testing of the yaw drive system consisted of the following operations and tests: setting and checking the dual yaw preload, verifying the operation of the hydraulic power unit, calibrating the time delay relay, evaluating nacelle response, deadband tests, tests to determine the yaw drive rate, and verifying system deactiviation. Prior to this assembly and testing, the yaw shafts were calibrated at the factory.

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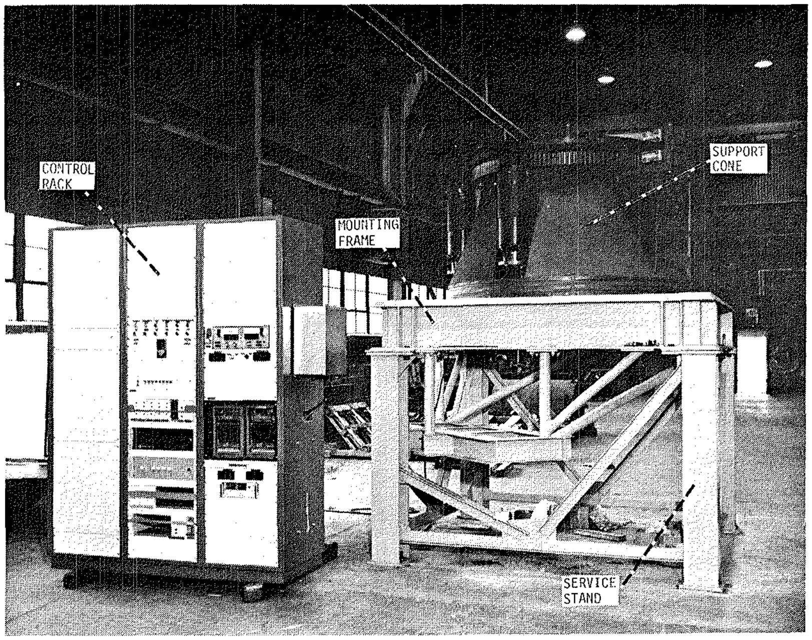

Figure 5.1.4-1. Service Stand, Mounting Frame, Support Cone, and Control Rack

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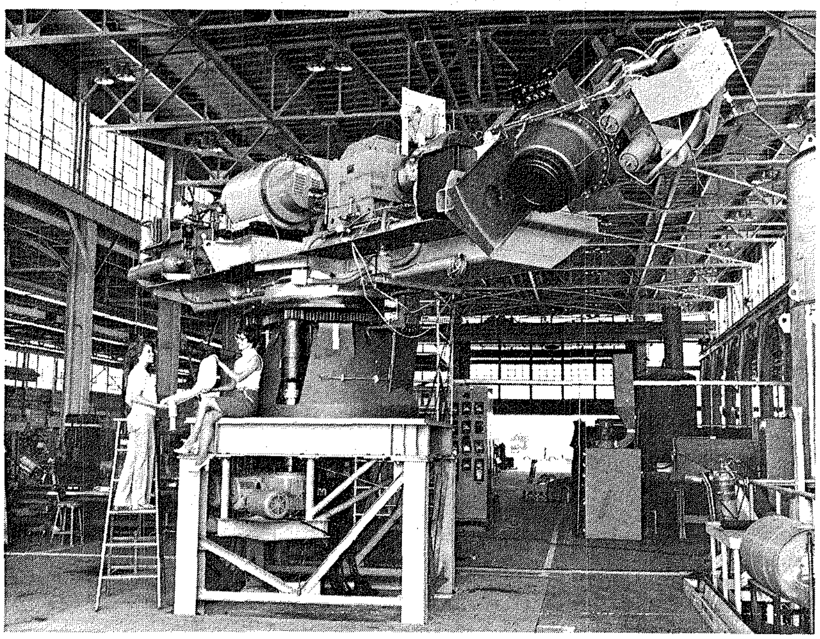

Figure 5.1.4-2. Photograph of MOD-OA WTG Assembly Prior to Phase III In Plant System Checkout Tests

During the operations for setting and checking the dual yaw preload, a shaft preload of 50,000 in-lbs. (5,650 Nm) was set into the dual yaw drive system. The bull gear was rotated 360° in both the clockwise and counterclockwise directions and the preload was recorded every 45° from the starting position. Satisfactory results were obtained from these operations.

For the verification testing on the operation of the hydraulic power unit, the hydraulic unit was set up to provide a hydraulic clamping pressure of 1500 psig (10.3 MPa) to the yaw brake when the system was not yawing. Also, a hydraulic drag pressure of 100 psig (0.69 MPa) was set up for the yaw brake during a yaw maneuver. A ±45° error signal was inputted to the controller and the correct operation of the clamping and drag pressures for the yaw brake was confirmed. During this testing, temperatures of the yaw motors, the yaw brake hydraulic pressures, and the preload at each data point or error correction time period were recorded. In addition, the yaw brake hydraulic pressure and yaw motor current were recorded on strip charts to confirm that the sequencing was in the proper order. Satisfactory operation of the hydraulic power unit was demonstrated.

The time delay relay was calibrated for range and proportion during yaw corrections in both the clockwise and counterclockwise directions. The relay was set for 10 seconds of time delay and this 10 second time delay was verified.

During the evaluation test on nacelle response, the system was started from rest and the anemometer wind vane was deflected in the clockwise and counterclockwise directions from a starting reference position, so as to calibrate the error signal required to initiate a correction in nacelle direction. The controller was set to correct when the angle between the nacelle direction and the wind vane direction was greater than the ±25 deadband. After setting up the controller to correct at 25° or greater, the tolerance between the nacelle direction and the wind vane direction after the controller has corrected nacelle position in both the clockwise and counterclockwise directions was determined. Satisfactory performance during this evaluation test on nacelle response was obtained.

With the yaw drive system and yaw control system components installed and operable, the deadband test involved the creation of an input error in the yaw control system by deflecting the nacelle wind vane and locking it in position so that it would not rotate with the nacelle rotation. The control deadband for the yaw drive mechanism is ±25°. From these tests, the error required to initiate control action in either direction was determined and the input error signal and the output response were tabulated. Correct operation of the yaw drive system and yaw control system was verified from these deadband tests.

The yaw drive rate tests were performed by inputting a wind vane error signal into the yaw controller and operating the yaw drive system for several complete revolutions in each direction. The yaw drive mechanism was designed to provide a yaw rate of 1/6 rpm (1.0°/sec). The test results confirmed the adequacy of the design for yaw drive rates. During these tests, the yaw drive motor currents and temperatures (while rotating in both directions and during reversals) were measured and recorded. Also, the amount of coasting after the drive motors were deenergized was measured and recorded. Satisfactory results were obtained and proper operation of the yaw drive system was demonstrated.

A verification test on system deactivation was performed to confirm that the yaw drive system is deactivated at wind speeds of less than 8 mph (3.6 m/s). This was accomplished both electrically and mechanically. Correct operation on deactivation of the yaw drive system was shown.

OVERALL SYSTEM CHECKOUT TESTS

Test No. 2 of the Phase III in plant tests consisted of a series of system checkout tests which included sensor installation and wiring verifications. As part of these system checkout evaluations, system continuity tests were conducted to verify that the engineering data acquisition system and the power and control circuits were installed correctly. These system checkout tests were performed in Building 50 (Fabrication Shop) at the NASA LeRC and included the use of the Mobile Data System.

Presented in Tables 8.1-1 through 8.1-4 are listings of the sensors for the engineering data acquisition system which are located on the rotor, drive train, nacelle/bedplate, and tower, respectively. Also, Tables 8.2-1 through 8.2-3 provide a listing of the sensor numbers which have input to the remote multiplexer units located on the hub, on the bedplate, and in the control building. The above tables delineate all of the instrumentation sensors for the data acquisition system which required verification of correct installation and wiring.

The system continuity tests were performed to confirm that all of the engineering data sensors and associated wiring were installed in accordance with the instrumentation drawings and that all of the power and control circuits were installed in accordance with the electrical and control system drawings. Some of the objectives of these system checkout tests were to ensure the following: a) proper sensor location in accordance with NASA Drawing Numbers CR758975 and CR758976, (W 1015F43), Electrical Sensor Locations; b) proper wiring in accordance with NASA Drawing Numbers CF758968, CF758969 and CF758970 (W 1016F01), Instrumentation Sensor Wiring List; c) proper measurement identification and recording range in accordance with NASA Drawing Numbers CF758978 (W 1016F04), Sensor Identification List; and d) demonstration of the accuracy capability for each measurement when the Mobile Data System is used for recording. The types of instrumentation sensors whose installation and wiring required verification were the temperatures, accelerations (for vibration measurements), pressures, strain gages, generator speed, low speed shaft position, and the current, voltage, output power (kW), VARS, and frequency for the generator. Standard instrumentation system checkout procedures were employed to confirm the correct installation and wiring of these sensors.

Several temperatures are measured at various locations in the MOD-OA WTG using copper-constantan thermocouples. The wiring and accuracy for each temperature sensor was checked by using an electrically operated icepoint substituted for each thermocouple. Then, the output voltage from each thermocouple was measured for the ambient temperature conditions. All temperature recording channels have a 20 mV full scale input with a 5.117 V output, for an overall gain of 256. The sensitivity of these thermocouples from 32°F to 80°F (0°C to 27°C) is 0.022 mV/°F (0.040 mV/°C). All icepoint temperature readings were

within the desired 1% voltage measurement uncertainty values. All thermocouple probes which were evaluated measured the ambient temperature within a range of 79°F and 89°F (26°C and 32°C). This range was considered reasonable based on possible temperature gradients within the system and the measurement uncertainty of the recording system.

Nine vibration measurement sensors are located at various positions on the drive train and at the top of the tower. These accelerometers generate a 10 V output for a 2G acceleration and the overall gain of the Mobile Data System for these measurements is 0.5117. Each measurement was checked statically with the accelerometer placed in three different positions: up, down, and horizontal. Based on the data derived, reasonable results were achieved and acceleration measurements within 1% of 2G were considered obtainable.

Four separate pressure measurements and their associated transducers were checked out for proper installation and wiring. Each measurement sensor was checked by pressurizing the transducer at 0, 500, 1000, 1500, and 2000 psig (0, 3.45, 6.9, 10.3, and 13.8 MPa), reading the pressure using a standard type pressure gauge, and comparing this reading with the reading for the pressure in the Mobile Data System. Nominal errors for the checkout of these pressure measurements were $<1\%$ full scale.

Several strain gages are located on the blades, low speed shaft, and bedplate. Two different procedures were employed for the system checkout tests on this instrumentation, since the blades and their gages were not available for verification. During the calibration and checkout of the strain gages for the low speed shaft and bedplate, a checkout output signal was compared to a previous calibration output signal. The data taken indicated nominal $<1\%$ full scale error results. For the blade strain gages, a calibration shunt checkout procedure was utilized.

Generator speed measurements were checked out using a signal generator in place of the magnetic pickup transducer, since the generator could not be rotated. From the test results derived, all errors were $<1\%$ of full scale.

The position of the low speed shaft during operation is obtained by using an optical sensor which detects white marks on a black tape that is wrapped around the shaft. Since the low speed shaft could not be rotated, only a steady-state test was performed. Proper operation of the three low speed shaft position measurements was demonstrated from these static tests.

The current, voltage, output power (kW), VARS, frequency, and field current for the generator are measured using transducers located in the switchgear. From the test data, proper installation, wiring, calibration, and accuracy capability were demonstrated.

Several exceptions were taken to the complete checkout of the instrumentation and data acquisition system. These exceptions included the following: a) the tower slip ring was not wired, b) dummy resistors were substituted for the blade strain gages, c) a signal generator was substituted for the magnetic pickups on the generator since the generator could not be rotated, and d) voltage inputs were substituted for the measurements where sensors were not available.

MICROPROCESSOR CHECKOUT

Checkout tests of the microprocessor hardware and software were also completed. This testing was performed by installing the microprocessor into the MOD-0 100 kW WTG system at Plum Brook. The microprocessor was used to run the MOD-0 WTG and final checkout and qualification tests were completed. From this testing, NASA LeRC confirmed the adequacy of the design and the associated hardware and software for the microprocessor.

5.2 SITE TESTS AND INSTALLATION

Several operations and tests were performed on the MOD-OA WTG at the Clayton, NM site during various stages of the final assembly, erection, and checkout of the components and systems. These tests and operations included a final checkout of the performance of the rotor, a systems checkout, testing of the drive train and nacelle equipment, and the installation experience (see Tables 5-2 and 5-3 and Figure 5-2). The various tests performed at the site have been categorized as they relate to a specific subsection of Section 5.2. Therefore, the tests performed and results derived during these tests, as presented in these subsections, do not represent a chronological completion of the installation, testing, and final systems checkout of the WTG prior to operation by the utility.

OPERATIONAL READINESS REVIEW TEAM

In conjunction with these site tests and installation, an Operational Readiness Review Team was assembled to verify the operational readiness of the MOD-OA at Clayton before the WTG could be turned over to the utility for operation. The primary task of the Readiness Review Team was to provide assurance that the following conditions existed:

- The as-built hardware complied with the design specifications and drawings.
- Adequate system checkout procedures were available and the operational readiness of the subsystems was verified.
- Adequate test and operating plans existed that included mandatory instrumentation requirements and limit values for critical parameters.
- Discrepancies had been reviewed and accepted, or corrective action had been taken.
- Adequate safety procedures existed and necessary safety training had been completed.

This Operational Readiness Review Team contributed significantly to ensuring that the Clayton WTG was ready for automatic, unattended, fail-safe operation as it was turned over to the utility. Included in these efforts were a review

of the operation and maintenance manual, a closeout of all discrepancy reports and engineering changes, a checkout of adequate training of utility personnel, and a review of the analysis of data taken during the site tests and the initial operation so as to confirm expected operating performance. All of the tasks and activities of the Readiness Review Team were satisfactorily completed.

PREPARATION FOR SITE TESTS

Several tasks were completed by the NASA LeRC, the system contractor, and the utility personnel in preparing for or performing the site tests on various components and systems and the final installation and checkout. These efforts were performed in accordance with an initial startup and operation procedure manual. These tasks were completed prior to, in conjunction with, or after the various site tests discussed below. While the complete WTG assembly was located on the service stand, the pneumatic systems were charged with nitrogen. The speed increaser, fluid coupling, and high speed bearings were checked for proper oil operating levels. The hydraulic pump reservoirs for the pitch change mechanism and the yaw brake were checked for proper operating levels of hydraulic fluid. The tower slip ring was installed and the high speed brake was C-clamped. A checkout of the hydraulic and/or pneumatic systems for the rotor brake, pitch change mechanism, and yaw brake was performed. The accelerometers on the tower were installed and checked out.

Before the WTG was installed on the tower, all power, control, and instrumentation wiring connections between the top of the tower and the control building were completed. Also, the connections to the transformer, oil circuit recloser, the utility, the remote control and monitoring system, and the Mobile Data System were performed. The lifting procedure of the WTG to the top of the tower and the final mechanical assembly were completed. The power, control, data acquisition, and yaw drive system terminations at the top of the tower were completed. Further details on some of these tasks have been provided in the subsections below.

5.2.1 ROTOR

The activities related to the site tests on the rotor assembly included the installation of the blades to the hub, a checkout of the instrumentation for the rotor assembly, and in particular the instrumentation sensors on the blades, and a verification of the operating capabilities of the pitch change mechanism and pitch control system.

BLADE INSTALLATION AND INSTRUMENTATION CHECKOUT

The blade installation was completed in accordance with NASA Drawing No. CF758930 (W 1015F59), Interface - Blade to Hub. During the acceptance testing and checkout of the MOD-OA blades, the twist schedule on blade number five was found to be outside of the required specifications. This blade was returned to Lockheed for corrective action. The twist angle error between midspan and the blade tip was corrected, and the blade was reinstalled into the rotor assembly at Clayton and properly checked out. Additional information on the installation of the blades is presented below in Section 5.2.4.

Some of the instrumentation sensors for the rotor assembly were tested and calibrated during the various in plant tests discussed above in Sections 5.1.2 and 5.1.4. The additional instrumentation for the rotor assembly which required final checkout at the site included the strain gages located on the blades. These blade strain gages were calibrated at the Lockheed plant. No detailed calibrations of these strain gages were performed at the site. However, a test was completed for these strain gages to ensure that the instrumentation wiring was properly connected with the correct polarity and that accurate data could be recorded from this instrumentation.

PITCH CHANGE MECHANISM AND DYNAMIC BALANCING

The operation of the pitch change mechanism, pitch hydraulic system, and pitch control system for the rotor assembly was previously evaluated during the in plant tests of Section 5.1.3. The operational capabilities of these components and systems were verified and demonstrated during those tests. In addition, a final checkout series of tests on the pitch control system was performed, as discussed in Section 5.2.2 below. During the manual startup and operation of the WTG located on top of the tower, a pitch control sub-mode of operation checkout test was performed, as presented below in Section 5.2.3.

During the in plant tests, static and dynamic balancing of the rotor assembly was completed, as discussed above in Section 5.1.2. The site tests performed on the rotor assembly without the blades included a dynamic balancing operation. Since these dynamic balancing tests were performed on the complete drive train assembly, in addition to the rotor, the results of these tests are summarized in Section 5.2.3 below.

5.2.2 SYSTEMS CHECKOUT

The site tests for the MOD-OA WTG included a series of checkout operations on the various systems. These systems checkout tests involved a verification of the yaw drive system, the completion of the electrical terminations at the top of the tower, a checkout of the safety shutdown system, checkout tests on the pitch control system, and system shutdown testing.

YAW DRIVE SYSTEM AND YAW BRAKE

For a complete reference of the applicable drawings, refer to NASA Drawing No. CF758971 (W 1016F02), entitled Power One Line Connection Diagram and Schedule of Drawings. During the verification and checkout of the yaw drive system, a two-man operating team, with one person located in the control room and the other located in the nacelle or at an elevation of 81 feet (25m), was utilized. Two-way communications were established for these checks. After securing an electrical power source for the yaw drive motors and for the hydraulic pump in the yaw brake system, checkout operations of the two drive motors and the yaw brake were performed. Each of the yaw motors was energized individually and manual command signals were made on the yaw control panel to rotate the bedplate in both the clockwise and counterclockwise directions. Confirmation of correct rotation and operation was made both visually and by the indications of the data acquisition system.

Checkout of the yaw brake hydraulic pump circuit was performed. During these checkout tests, the hydraulic pump motor was energized and operated through a typical startup and shutdown sequence. Final checkout tests of the control circuits for the yaw drive system and of the drag pressure on the yaw brake during yaw maneuvers were completed. The preload torque for the yaw drive mechanism was verified. The absolute yaw torque during manual operations of the yaw drive system was evaluated and correct operation was confirmed. During yaw maneuvers, the absolute yaw torque indication was monitored to ensure that the value did not exceed 90,000 in-lbs (10,200 Nm). The above operations and testing were performed in both the clockwise and counterclockwise directions.

The automatic mode of operation for the yaw control system was also evaluated. First, the nacelle was rotated (using the yaw drive motors in their manual position) to a 45° angle from the actual wind direction. Then the yaw control system was placed in the automatic mode. Correct operation of the yaw drive system to align the nacelle with the wind vane located on the nacelle was confirmed. The above testing constituted all of the verification and checkout tests performed on the yaw drive mechanism, yaw brake, and yaw control system. From the test results derived, satisfactory operation was demonstrated.

FINAL TOWER TERMINATIONS

After the complete WTG assembly was mounted on top of the tower, final electrical, control, and instrumentation terminations were completed. In conjunction with these operations, the appropriate field safety procedures were followed. All electrical circuits to the top of the tower were turned off by placing the applicable circuit breakers in the off position. The remaining wiring between the tower slip ring and the auxiliary electronic package, the terminal boxes, and the low speed shaft slip ring were all completed in accordance with the appropriate drawings. Also, the previously installed tower accelerometers were wired to the appropriate terminal box.

SAFETY SHUTDOWN SYSTEM AND DISK (ROTOR) BRAKE

A series of checkout tests of the Safety Shutdown System was performed. These verifications included a checkout of the appropriate shutdown parameters to achieve a Critical, an Emergency, or a Redundant Shutdown. A Critical Shutdown operation occurs when one of the overspeed switches (which is in the normally closed position) is opened as the rotor speed exceeds 45 rpm. During a critical shutdown, the disk (rotor) brake is engaged. Checkout operations on the performance of the disk brake were also completed.

During these checkout operations on the disk brake, various testing was performed. Initially, the pneumatic system for the disk brake was checked to verify proper setup for operation. A strip chart recorder was used for monitoring the following parameters during the disk brake tests: wind speed, rotor speed, blade flap and chord moment, input torque, shaft bending, and brake pad temperature. Also, the bottle pressure for the brake was logged before and after each test. With the strip chart recorder operating, the rotor was brought up to a speed of five rpm and maintained at that speed for two minutes. Then, the WTG was shut down by activating a critical shutdown. After

the rotor stopped rotating, the strip chart recorder was turned off and the brake pad temperature was monitored manually until a stable condition existed. Test data were reviewed to ensure that the red line values for the various parameters were not exceeded. The above testing was repeated for rotor speeds of 10, 25, and 40 rpm. During this testing and checkout operation, satisfactory results were demonstrated, including the activation of the appropriate alarm signals.

For an Emergency Shutdown to be executed, the following parameters and instrumentation sensors are monitored: vibration, bottle pressure, hydraulic level, yaw error, overcurrent and reverse power, watch dog timer, overtemperature, adjustable overspeed, intrusion alarm, and pitch hydraulic pump pressure. The Redundant Shutdown conditions include requirements to monitor wind speed, wind direction, and the redundant nacelle sensors for vibration, disk (rotor) brake bottle pressure, and feather bottle pressure.

Extensive initial startup and operation checkout procedures were performed on each of the above shutdown parameters for the critical, emergency, and redundant shutdown conditions. Satisfactory operation was demonstrated as a result of these checkout tests. During the checkout tests on the rotor brake, correct operation of the high speed brake pads was verified. The operation of the redundant solenoid valves was also confirmed.

PITCH CONTROL SYSTEM

Checkout operations were performed on the pitch control system to verify that the blades could be feathered as designed. Appropriate procedures were followed, in conjunction with NASA Drawing No. CF759027 (W 1016F12), entitled Control Elementary Diagram, and the Manual Control Panel Layout and the Pitch Controller Panel Layout. Various manual operations of the pitch control system were completed and correct pitching of each of the blades was verified by observation. The emergency shutdown system at the microprocessor was tripped, and the shutdown of the pitch hydraulic pump and the deenergizing of the fail-safe solenoids was confirmed. Also, during a redundant shutdown and a critical shutdown operation, the correct performance of the pitch control system was verified. This included testing of the redundant safety shutdown system at the nacelle. Proper operation of the pitch control system was confirmed during actual rotating tests of the low speed shaft and rotor.

MANUAL AND AUTOMATIC SHUTDOWN

In addition to a safety shutdown, two other shutdown modes apply to the system: manual and fully automatic (microprocessor). Depending upon which mode and/or submode of operation for the WTG, there is a desirable way in which to shut down the system. The following procedure is used during a manual shutdown operation: a) the load setpoint at the pitch controller is decreased to a value of 50, b) a speed setpoint pot setting of 800 is verified (this corresponds to 40 rpm), c) the speed/load switch is placed in the speed position, d) the line breaker "open" push button is depressed, e) the field contactor "open" push button is depressed, f) the speed setpoint pot is reduced

to a value of 100 (this corresponds to a rotor speed of five rpm), g) the manual setpoint pot is adjusted to match the servo-amp position meter, h) the auto/manual/ ext. switch located on the pitch control panel is placed in the manual position, i) the manual pot setting is decreased to 000, j) verification that the rotor has stopped (zero rpm) is made, k) verification that the blades are feathered is made, and l) all systems are secured. A manual shutdown of the WTG was performed in accordance with this procedure and satisfactory results were obtained.

An automatic or microprocessor shutdown operation was also completed during the system checkout tests at the site. A microprocessor shutdown was performed using the following steps: a) the stop button on the microprocessor was pushed and b) after the rotor came to a full stop, the switch located on the manual control panel was placed in the off position.

From all of the above results on system checkout tests; correct operation of the MOD-OA WTG was verified for the various safety shutdown conditions, as well as for the manual and microprocessor shutdown capabilities.

5.2.3 DRIVE TRAIN AND NACELLE EQUIPMENT

Several tests were performed at the site on the drive train and on the equipment located within the nacelle. Initially, the drive train and nacelle equipment (including the bedplate, support cone, mounting frame, and hub assembly without the blades) were mounted on the service stand. Rotating tests were performed on the drive train assembly, including a final checkout test of dynamic balancing. After the blades were mounted on the hub and the stationary and rotating parts of the nacelle enclosure were installed, the WTG was lifted to the top of the tower and secured, and final terminations were completed. Then, manual startup and operation of the WTG was performed. The final series of tests involved checkout operations with the microprocessor.

DYNAMIC BALANCING

As discussed above in Section 5.1.1 (In Plant Tests on the Drive Train and Nacelle Equipment) and Section 5.1.2 (In Plant Tests on the Rotor), dynamic balancing operations of the drive train assembly and of the hub assembly were performed. During the site tests on the MOD-OA WTG, a final checkout on the dynamic balance of the drive train assembly, including the hub without the blades, was performed. For these site tests, various accelerometers and vibration instrumentation were located on the low speed shaft, pillow block bearings on the high speed shaft, and at other locations in the drive train assembly. Data from this instrumentation were monitored and recorded. The final peak-to-peak vibration amplitude results were comparable to the results derived during the in plant tests. Thus, the final checkout tests for dynamic balancing were satisfactorily completed.

MANUAL AND AUTOMATIC STARTUP

After the WTG was mounted on top of the tower and final terminations for all of the electrical, control, and instrumentation wiring were completed, a series of initial startup tests was performed for manual and automatic startup and

operation. A pre-startup verification and checkout procedure was completed to ensure that all components and systems were operational. A manual startup was performed in which the capability of the pitch control sub-mode of operation was confirmed. Next, tests were conducted on the speed control sub-mode of operation during manual startup. Finally, the load control sub-mode of operation, in which the output power is synchronized with the utility network, was tested manually. The output power was maintained for at least 15 minutes at 25, 50, 100, 150, and 200 kW. A strip chart recorder was used to monitor wind speed, rotor speed, blade flap and chord moments, imput torque, shaft bending, and brake pad temperature. Other temperatures and system pressures were also monitored. The test results were reviewed to insure that the red line values for the above parameters were not exceeded during these initial startup tests. Satisfactory results from these pitch, speed, and load control modes of manual operation tests were demonstrated.

Automatic startup and operation tests of the WTG, with the use of the microprocessor for automatic control, were also conducted. After an initial checkout of the operational readiness of the microprocessor and automatic control system, automatic startup and operational tests were performed and satisfactory performance of the microprocessor was demonstrated.

5.2.4 INSTALLATION EXPERIENCE

The installation of the MOD-OA at the Clayton site involved the following operations: site preparation, pouring of foundations, tower erection, assembly of control building and equipment within the building, reassembly of drive train to support cone, blade installation, installation of the equipment and personnel hoist, blade installation, lifting of the WTG to the top of the tower, and the power, control, and instrumentation wiring and hookup (see Table 5-3 and Figure 5-2).

SITE PREPARATION AND POURING OF FOUNDATIONS

Site preparation activities performed by the utility included providing an access road, a security fence around the site, and the electrical interface equipment. Excavations were made, reinforcing steel and anchor bolts were installed, and concrete foundations were poured to support the tower, service stand, control building, transformer, and oil circuit recloser. These tasks were performed by the system contractor. The installation procedures on site preparation and the pouring of the foundations were satisfactorily completed.

Shown previously in Figure 4.5.2-4 was a photograph of the reinforcing steel rods for the tower foundation before the concrete was poured. Presented in Figure 4.5.2-3 was a photograph of the concrete foundation for the tower structure and control building. A photograph of the tower leg mount in the foundation for the tower was shown previously in Figure 4.5.2-5.

INSTALLATION OF TOWER, CONTROL BUILDING, AND OTHER EQUIPMENT

Before the tower was assembled and erected at the site, a final checkout and assembly operation of the tower components was performed at the manufacturer. Shown previously in Figure 4.5.1-2 was a photograph of the final assembly

operations performed on the tower at the manufacturer's facility. The assembly of the MOD-0A tower at the site was shown in Figure 4.5.1-3. The tower was erected on the foundation with the use of a crane. Shown in Figure 5.2.4-1 is

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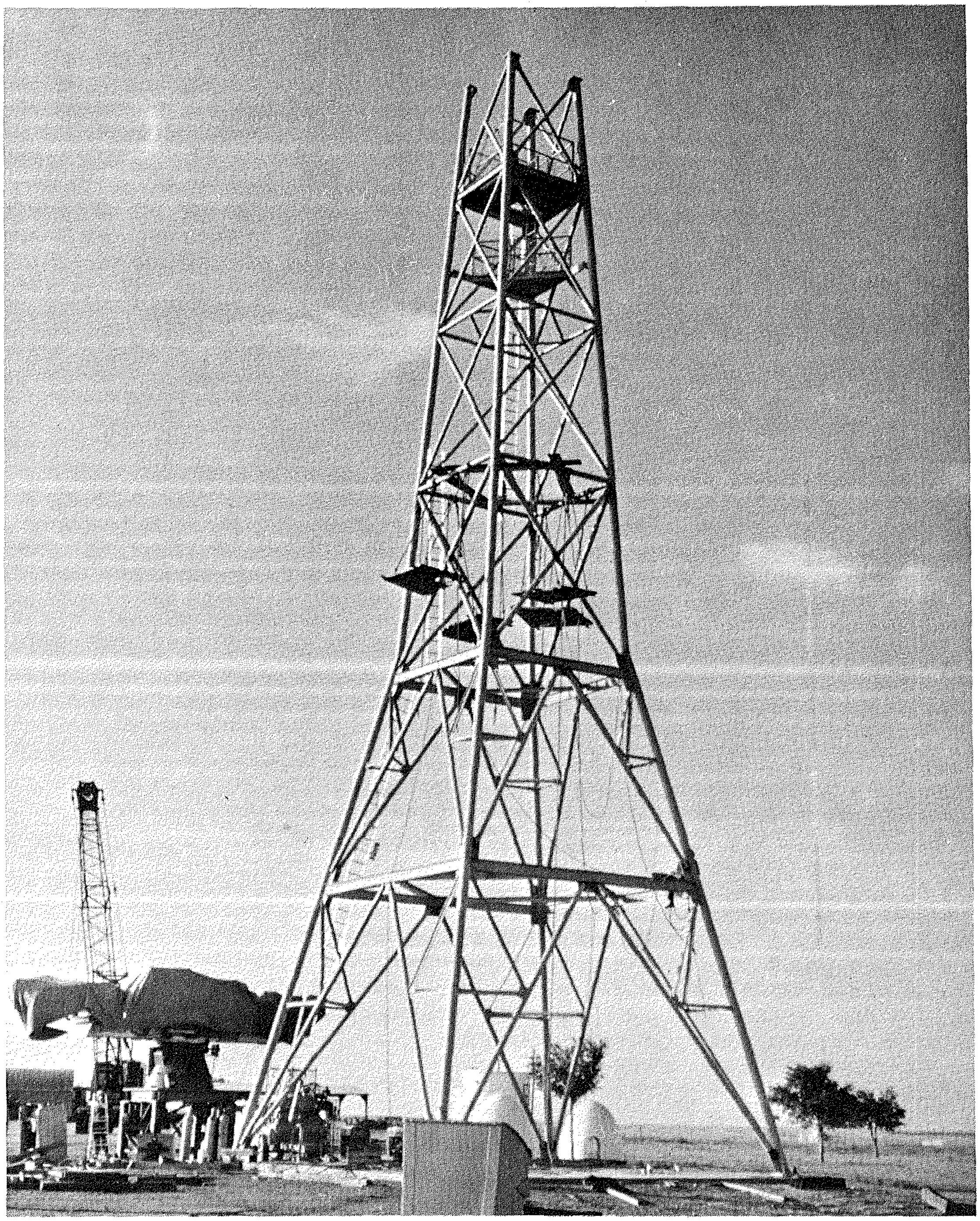

Figure 5.2.4-1. Installation of MOD-0A Tower on Foundation at Clayton, NM.

a photograph of the final installation of the MOD-OA tower at the Clayton site. Also included in the photograph is the drive train assembly and support cone mounted on the service stand. This service stand was used for final checkout and operation of the WTG before the completed assembly was mounted on top of the tower.

The control building was assembled at the base of the tower. The various power, control, and instrumentation components and systems located within the control building were installed. Installation and hookup of the oil circuit recloser (see Figure 4.6.3-1) and the transformer (see Figure 4.6.3-2) were completed. The remote control and monitoring system, shown previously in Figure 4.7.7-1, was installed at the utility.

Presented in Table 8.1-6 was a listing of the wind speed, wind direction, and ambient temperature sensors located on the meteorological tower. These meteorological tower sensors and other sensors, as listed in Table 8.2-3, were connected to the remote multiplexer unit located in the control building. A tabulation of the instrumentation and data acquisition channels which were connected to the Stand Alone Instrument Recorder (SAIR) was presented in Table 8.4-1. Installation procedures for the control building and meteorological tower included the appropriate wiring for hookup of the above data acquisition sensors and the placement of various components within the control building. Also, the equipment and personnel hoist was installed to permit access from ground level to the top of the tower. Shown previously in Figure 4.5.4-1 was a photograph of this cable-mounted equipment and personnel hoist system.

REASSEMBLY OF DRIVE TRAIN TO SUPPORT CONE AND BLADE INSTALLATION

The support cone, service stand, and associated components (yaw drive mechanism, yaw brake, mounting frame, and turntable bearing) were installed on the concrete foundation for the service stand. The drive train assembly (bedplate, hub, low speed and high speed shaft components, speed increaser, pitch change mechanism and pitch hydraulic system, and generator) was reassembled onto the support cone/service stand. Then, the blades were installed to the hub of the rotor assembly. This installation included the use of wooden saddles, a clamshell device, and a lifting beam to support the blade, as each blade was being mounted on the hub. Additional information on the installation and checkout of the blades and its associated instrumentation was discussed above in Section 5.2.1. Shown previously in Figure 4.1.1-1 was a photograph of the final assembly operations of the nacelle prop cone after the blades had been installed.

LIFTING OF WTG TO TOP OF TOWER

Lifting of the complete WTG assembly (rotor, blades, drive train, bedplate, support cone, nacelle, and mounting frame) to the top of the tower was accomplished with the use of a crane. Detailed procedures were developed and followed for this lifting operation. Shown previously in Figure 4.5-1 was a photograph of this lifting operation during the installation of the complete WTG assembly on the top of the tower. A photograph of the final stage of this WTG lifting operation and the installation to the tower is shown in Figure 5.2.4-2.

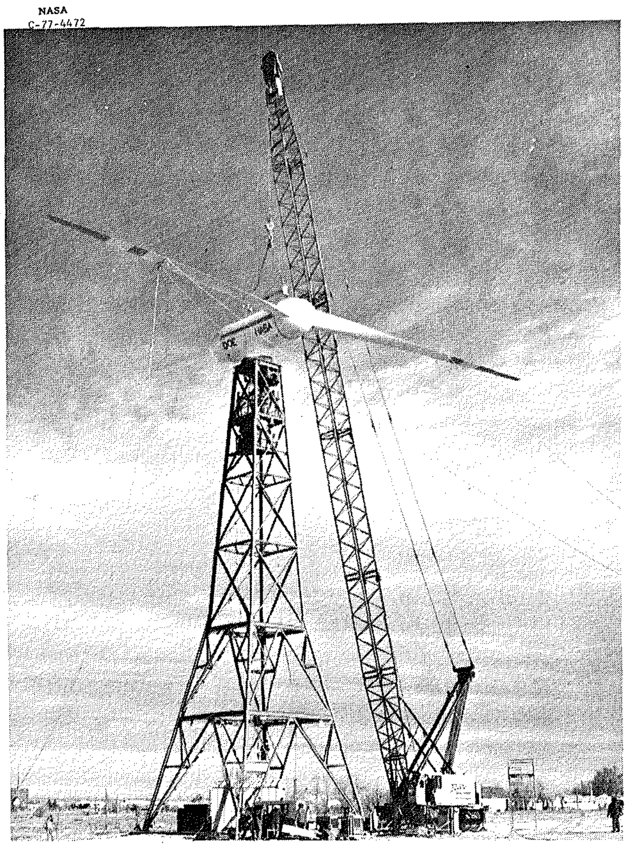

Figure 5.2.4-2. Final Stage of WTG Lifting Operation and Installation to the Tower

POWER, CONTROL, AND INSTRUMENTATION HOOKUP

Subsequent to the completion of the lifting procedure and the attachment of the mounting frame to the top of the tower, the electrical, control, and instrumentation terminations were completed. Final checkout of all of the mechanical, electrical, control, instrumentation, and safety systems was performed, as discussed above in Sections 5.2.1 through 5.2.3. Finally, a security fence was installed around the MOD-OA WTG tower to permit safe, automatic, unattended operation.

FIRST ROTATION, DEDICATION, AND TURN-OVER TO UTILITY

All of the above site tests and the installation of the MOD-OA WTG at Clayton were satisfactorily completed. First rotation of the MOD-OA WTG was performed on November 30, 1977 and the wind turbine was formally dedicated on January 28, 1978. On March 6, 1978, the WTG was turned over to the Tower of Clayton Light and Water Plant for utility operation, including automatic, unattended operation.

6.0 SAFETY CONSIDERATIONS

Safety considerations in this section include a discussion of the safety philosophy used in the MOD-OA design, construction, and operation; a description and evaluation of the Clayton Site; the design criteria; the normal and emergency operating procedures; identification of hazards and an evaluation of the probability of occurrence and their predicted consequences; physical features of the design; safety related administrative controls; and an analysis of the potentially most dangerous accident.

6.1 SAFETY PHILOSOPHY

Modern wind turbines such as the MOD-OA machine are a combination of centuries old windmill technology, standard commercial practices of the electric power and steel construction industry, and advanced aerospace technologies related to helicopter rotors, computer analyses, materials, etc. As such, the wind turbine should be relatively hazard free if the safety techniques developed in the aerospace industry are applied in a judicious and systematic manner while recognizing both the unique and standard commercial characteristics of the MOD-OA machine.

The MOD-OA safety program identified, evaluated, and either eliminated or controlled all undesirable hazards with potential to injure the general public or operating personnel, damage the system or support equipment and facilities, or cause loss of program objectives. These objectives of the safety program were accomplished by: a) identifying the equipment, functions, and operations that possibly could result in hazards, b) assessing those hazards for impact and probability, c) instituting methods to eliminate hazards or reduce them to an acceptable risk level, and d) verifying the implementation of control measures in design, operating controls, and procedures for installation, test, and maintenance.

Appropriate safety disciplines were integrated into the MOD-OA design process throughout the design cycle. They were an integral part of the design from the initial MOD-0 concepts, through the evolution to MOD-OA, and throughout all phases of the MOD-OA design, construction, testing, and operation.

The safety design philosophy was that no major damage should occur during the service life of the machine because of a single-point failure or a single failure following an undetected failure. The "fail-safe" approach was employed. All major safety related systems were provided with redundant and diverse backup systems.

Considerably more detail is available in the literature on safety considerations related to the design and operation of large wind turbines.[53]

6.2 SITE DESCRIPTION AND EVALUATION

The site is located near the town of Clayton, in the extreme northeast corner of New Mexico, about 15 miles (24 km) west of the Texas border. Winds at

Clayton average 12 mph (5.4 m/s) at 30 ft (9.1 m) on an annual basis. Data indicate winds in excess of 46 mph (21 m/s) occur only two percent of the year (175 hours). Most such occurrences are during thunderstorms in summer and during blizzards in winter. The site is described in additional detail in Section 1.2.2 and in the environmental assessment report.[54]

6.3 DESIGN CRITERIA

6.3.1 DESIGN REQUIREMENTS

The safety related general design criteria are that no major damage or personnel hazard should occur because of a single point failure or a single failure following an undetected failure.

Overall system design requirements are given in Section 3.1 along with environmental conditions applicable during operation, storage, installation, and transportation. Additional detail design requirements are discussed in Sections 4.0 and 8.0. For example, structural loads, allowables, and safety factors or margins are in Section 4.8, while the instrumentation and control system criteria are in Sections 4.7 and 8.0.

6.3.2 COMPLIANCE WITH STANDARDS AND REGULATIONS

All appropriate standards were satisfied during the design and construction of the Clayton wind turbine. Also, operations satisfy the proper standards. As examples, the support tower and foundation were designed to American Concrete Institute and American Institute of Steel Construction codes, the electrical system was designed to the National Electrical code, and the generator was purchased according to NEMA standard MG1. During construction and operation, all OSHA requirements were satisfied.

6.3.3 SITE SAFETY

The site safety plan is composed of the NASA Safety Permit No. 8-175 dated January 15, 1978 the City of Clayton, New Mexico Safety Plan dated November 30, 1977, and the emergency plan in case of injury and inoperative manlift (spider shafter). These safety plans are reproduced in Appendix B.

6.4 NORMAL AND EMERGENCY OPERATING PROCEDURES

A detail manual was developed for normal and emergency operating procedures. A very brief summary of this manual follows.

Normal operation of the wind turbine generator is performed via the remote control and monitoring system from the master control station within the utility dispatcher's office. However, prior to start of operation, preliminary operational checks must be made at the wind turbine site. When entering the wind turbine site, definite entrance procedures must be followed to ensure the safety of all operating and maintenance personnel. The major areas of concern are the control building and the nacelle.

After verifying that personnel are away from the tower and out of the nacelle, a detailed electrical and mechanical checklist is followed before operation can be performed by the utility dispatcher. With the dispatcher in control, the turbine is started using microprocessor control. The dispatcher then maintains control and shuts down the machine when appropriate.

If the automatic or normal manual shutdown does not occur, the emergency shutdown system can be activated by the dispatcher as described in the manual.

Section 4.7 describes the control system in detail. It describes what sensors automatically shut down the WTG and what happens electrically and mechanically when the emergency system is activated.

6.5 IDENTIFICATION OF HAZARDS

Hazards identified have been placed into three groups. The first two are the obvious hazards and the hazards identified by the Safety Committee. These are discussed in the following two sections. A systematic identification of hazards is part of the FMEA in Section 7.0.

6.5.1 OBVIOUS HAZARDS

Five obvious hazards exist for the Clayton MOD-OA wind turbine. These are tower collapse or component blow-off, blade failure, ice thrown from the blades, aircraft collision, and injury due to unauthorized access.

1) Tower Collapse or Component Blow-Off

   In the event of tower collapse or component blow-off, the wind turbine or component may fall in any direction. Maximum horizontal extension of the turbine if the rotor retained its integrity would be 165 feet (50.3 m). Since the rotor would be feathered and braked far in advance of the occurrence of wind speeds exceeding tower design limits (in excess of 125 mph [55.9 m/s]), blade throw is not expected to accompany tower collapse. However, the rotor may break due to striking the tower or the ground and may therefore increase the area of impact, depending upon the orientation of the rotor and the attitude of tower collapse.

2) Blade Failure

   Computations summarized in Section 6.8 indicate that an unrestrained blade could be propelled up to 630 feet (192 m) from the tower base if it broke away from the hub at 55 rpm and at optimum blade throw angle. Pieces of the blade in the tip area could travel even further than this. Blade throw distance would be significantly reduced if shedding occurred at less than optimum blade angle. At about 55 rpm, the blade attachment bolts are expected to fail.

   Since the wind turbine is 173 feet (52.7 m) from the fence of the nearby county fairgrounds and 461 feet (141 m) from a residential fence and the

ballpark, a thrown blade could potentially cause serious accidents - especially at fair time.

3) Thrown Ice

In the event of blade icing, large chunks of ice could be thrown considerable distances in the plane of rotation depending upon the blade rotation speed, break-away angle, ice mass, and aerodynamic shape.

4) Aircraft Collision

The wind turbine site is within two miles of the Clayton airport. Thus, the potential exists for collision with low flying aircraft.

5) Injury Due to Unauthorized Access

Safety risks associated with unauthorized access to the wind turbine include falls from the tower and injury caused by coming into contact with electrical power equipment near the wind turbine.

6.5.2 SAFETY COMMITTEE CONCERNS

The major concern of the Safety Committee was the possibility of a blade separation. Blade failure is the only serious hazard that could result from a single failure - the blade itself has redundant structural members but the member mounting the blade to the hub is not redundant. The potential risk associated with a blade failure is described in Section 6.5.1. Other concerns were related to high measured MOD-0 blade load, marginal fatigue life for the blade, spindle, and hub, and questionable overspeed protection.

6.6 PROBABILITY OF OCCURRENCE AND PREDICTED CONSEQUENCES

The predicted consequences and probability of occurrence are discussed below for the obvious hazards and the Safety Committee concerns. The FMEA in Section 7.0 is a systematic discussion of consequences of failures of all significant systems and components.

1) Tower Collapse or Component Blow-Off

Tower collapse is considered highly unlikely, even during periods of extremely high winds. The only conditions which are viewed as potentially hazardous are tornadoes or freak gusts which far exceed design limits.

Other possible causes of tower collapse include foundation undermining due to flooding or ground settling, or a sudden geologic calamity such as an earthquake. Foundation undermining would be a relatively gradual process and would be noted and corrected during regular maintenance and inspection activities. Tower loading expected from ground acceleration forces associated with a nearby earthquake of up to seven on the Richter

scale are less than those associated with high wind loading and are not a significant danger with structures of this type, although some risk cannot be discounted.

The risk to technical personnel or visitors near the wind turbine is not expected to be high in the event of tower collapse or component blow-off, due to the extreme severity of conditions which would precipitate the risk. It is highly unlikely that people would be in exposed areas near the wind turbine during periods when winds approached or exceeded 125 mph (55.9 m/s) or during a tornado "warning" period. During an earthquake, the turbine would pose less risk than many other structures due to its high structural integrity, relatively low mass, and the absence of loosely attached overhangs or facades.

2) Blade Failure

Given the safety and design features incorporated into the MOD-OA wind turbine, blade failure is highly unlikely. Two additional factors limit the potential for injury of people: 1) the turbine will not be rotating when wind speeds exceed 40 mph (18 m/s) at hub height and 2) it is not probable that people (particularly visitors) will be in exposed areas within or near the exclusion radius during high wind or storm conditions.

Safety features and precautions instituted to identify structural problems and decrease the risk of blade failure include 1) automatic monitoring of the turbine's operational performance and structural dynamics, 2) automatic shutdown and required manual restart in the event a structural imbalance becomes evident, and 3) regular inspections and maintenance. As an additional precaution, and to protect the machine structure, the blades are feathered and braked when wind speed exceeds 40 mph (18 m/s). The rotor has been designed to withstand wind speeds in excess of 125 mph (55.9 m/s) at 30 ft (9.1 m) in a feathered position.

To minimize the risk of blade failure, sensors are installed on the wind turbine tower and automatically monitored. A structural problem which develops during turbine operation or an unusual load will be signalled by excessive vibrations or a dynamic imbalance in the turbine and the machine will be automatically shut down before the problem becomes severe. Restart of a turbine which is shut down due to structural imbalance will have to be accomplished manually, and, since operation of an imbalanced machine would be instantly reaborted by the automatic safety devices, startup would require correction of the problem.

Even with these design features, the Safety Committee's concern with a thrown blade led to the consideration of providing a blade arrestor system that would catch the blade if it failed. This approach would provide a redundant and diverse mechanism to prevent blade throw. Two

failures would have to occur before blade separation. In addition, an undetected failure of the primary blade support structure could not occur as the turbine could not function with a primary failure. A conceptual design was proposed for the arrestor system based on a Kevlar cable within each blade.

The arrestor system was not incorporated into the design because the probability of a thrown blade was reduced to an acceptably low level by the following design features:

a) Blade loads were reduced significantly from the MOD-0 loads through tower design changes which reduced the tower shadow.
b) Hub and spindles have an infinite calculated fatigue life.
c) The blade has a calculated fatigue life exceeding 10 years at the maximum design wind velocity.
d) System design provides fully redundant and diverse overspeed protection.
e) Frequent inspections of the critical areas.
f) Redundant rotor overspeed shutdown setpoints are set at 42 and 45 rpm, well below the postulated 55 rpm failure point.

3) Thrown Ice

The safety feature that precludes problems with significant quantities of thrown ice is the vibration monitor, located on the low speed shaft bearing housing, which will cause shutdown at excessive loads. Blade icing may be uneven causing excessive vibrations. Even if the icing is the same for both blades, ice thrown from one blade (it is not plausible that equal masses of ice would be thrown from each blade simultaneously) would create an imbalance and the vibration sensor would shutdown the system.*

4) Aircraft Collision

The wind turbine nacelle and blades are painted orange and white for high visibility during daylight hours. The turbine is located 762 feet (232 m) away from the much taller KLMX radio tower [365 feet (111 m)]; thus, the aircraft warnings for this tower also give protection for the turbine.

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* In March, 1978, blade icing occurred on the wind turbine blades. At that time operating personnel first observed large pieces of ice, scattered on the ground, adjacent to the wind turbine. It was then observed that ice was shedding from the blades, while the blades were rotating at 40 rpm. This situation posed a safety hazard for personnel and equipment. For this safety reason, an ice detector system was installed on the blades to sense ice formation and initiate shutdown of the wind turbine generator. An aircraft type ice detector (Rosemount Inc. Model 871FA-122) was tested satisfactorily in the NASA LeRC Icing Research Tunnel. After the ice detector was installed in the blades during November 1978, it performed as expected. No further instances of ice thrown from the blades were observed.

5) Injury Due to Unauthorized Access

Safety risks associated with unauthorized accesses to the wind turbine are controlled by a fence around the site, elimination of footholds to discourage climbing of the tower, and positioning the cable-hung hoist sufficiently high to make it inaccessible from the ground level. All ground level electrical equipment will be shielded in compliance with OSHA regulations.

6.7 SAFETY RELATED PHYSICAL DESIGN FEATURES AND ADMINISTRATIVE CONTROLS

6.7.1 PHYSICAL FEATURES

The major safety related physical design feature is the safety shutdown system. Its description follows.

The safety shutdown system is an emergency shutdown system which can operate independently of all other control systems. A set of sensors connected with this system monitors potential problem areas, typically redundantly, to protect the machine from catastrophic failure.

The sensors monitor:

1. Overspeed
2. Overcurrent or reverse power
3. Vibration
4. Yaw error
5. Pitch system hydraulic fluid level and pressure
6. Bottle pressures
7. Temperatures
8. Microprocessor failure
9. Intrusion

Overspeed is sensed redundantly. The primary signal is an electronic sensor monitoring the speed increaser high speed shaft which is the WTG speed control signal. A redundant shutdown path is activated by a mechanical overspeed switch downstream of the fluid coupling, combined with an electronic detector sensing slip across the coupling, six percent max, and overspeed on each side of the coupling.

Overcurrent and reverse power are sensed by four relays, one reverse power and three phase overcurrents. All sensors are inputs to the safety shutdown card file; additionally, one overcurrent relay is used in a redundant shutdown path.

Vibration is detected by mechanical vibration sensors, one driving the safety shutdown card file, one in the redundant shutdown circuit.

Yaw error is determined by two methods. The primary system, driving the safety system card file, detects an error between the nacelle wind vane and the nacelle, and initiates a shutdown if a forty degree error is exceeded for ten seconds. The redundant path detects an error between the nacelle direction and the weather tower wind direction, with shutdown through the redundant path if a ninety degree error is detected. Both signals are defeated during low wind speeds.

Pitch hydraulic level is a nonredundant shutdown through the safety shutdown card file. Redundancy is provided through hydraulic pressure monitoring and bottle pressure shutdowns.

Bottle pressure for the pitch system and rotor brake are measured redundantly, with shutdown capability through the card file and the redundant path. Additionally, yaw brake pressure, both under and over pressure, is monitored.

Temperatures are measured nonredundantly, with shutdown through the safety system card file.

Microprocessor failure is detected if the microprocessor fails to reset a timer as it cycles through its program.

Intrusion is monitored by a security system which initiates a safety shutdown upon unauthorized entry.

The safety shutdown card file records the fault initiating a shutdown, transfers this data to the remote control and monitoring system, and initiates a shutdown. The redundant path bypasses the card file. The emergency shutdown procedure turns off the hydraulic pump, activates emergency feather, and after a time delay, turns off the generator field and desynchronizes the system. Overspeed shutdowns also engage the rotor brake. After a shutdown, the system can only be restarted at the wind turbine site.

The remote control and monitoring system is designed to allow the utility dispatcher to monitor the wind turbine status and control its operation, through the microprocessor. The monitoring systems fall into two classifications, analog and discrete. Analog channels monitor the wind speed, rotor speed, power output, VARS, voltage, and current. They are displayed in a digital voltmeter format. Discrete on-off indications monitor the WTG and safety system status. The discrete channels are:

- Auto/Man operation
- Blades feathered
- Overspeed
- Yaw error
- Overtemperature
- Overcurrent/Reverse power
- Excessive vibration
- Hydraulic system fault

The remote control function is limited to a start-stop command to the microprocessor. The microprocessor will then automatically control the wind turbine according to its program.

The other safety related physical design features, as well as additional details of the safety shutdown system, are discussed in Section 4.0.

6.7.2 ADMINISTRATIVE CONTROLS

The major administrative controls applied to this project were through a Safety Committee and quality assurance procedures.

6.7.2.1 SAFETY COMMITTEE

The safety committee met regularly to review all phases of the project from a safety viewpoint. It was composed of senior technical and management personnel with expertise in all areas related to wind turbine generators. A safety permit issued by this committee was required before each phase of the project -- construction, testing, and operation. A copy of the operating safety permit is reproduced in Appendix B.

6.7.2.2 QUALITY ASSURANCE PROCEDURES

Strict quality assurance procedures controlled the NASA LeRC in-house design and construction effort, the field construction work, and site operation.

The quality assurance procedures were a blend of those used at NASA LeRC for launch vehicles, spacecraft, and aircraft engines and those normally used for electromechanical industrial components. Their objective was to achieve a safety level close to that of aerospace projects at the low cost of normal industrial practice. For example, the LeRC performed portion of the project included procedures for design and reliability control, configuration control, procured article control, LeRC in-house controls, inspection, and failure reporting. A detailed discussion is given in Reference 55.

6.8 ANALYSIS OF POTENTIAL ACCIDENTS

As described in Sections 6.5 and 6.6, blade failure is the only serious accident with any credibility of occurring. It is also the only potentially serious accident that requires nontrivial analysis.

Analysis was performed by R. E. Ricker of the Southwest Research Institute under a NASA LeRC contract to predict the distance traveled by a blade after separation at its root. A summary of this analysis follows.

The purpose of the analysis was to predict the distance traveled by a MOD-OA blade which has failed at its root, with its trajectory in the machine's plane of rotation. The velocity at which it impacts the ground was also calculated in order to estimate the extent of damage to a nearby structure which might be struck by the blade.

It is most likely that the blade will tumble through the air with drag and gravity acting upon it, but with little, if any, net lift. However, three types of trajectories were considered. These are all unrealistic, but the distances calculated for these three cases are probably larger than the distance traveled by a blade with its most likely kind of behavior. These three trajectories are:

Case 1. The blade is treated as a long rectangle with the flow end-on, from the time of failure until impact. Drag and gravity act upon the blade, but there is no lift. The drag coefficient is based upon the average cross-sectional area of the blade.

Case 2. The blade rotates about its spar axis, sort of screwing itself through the air. No way of accurately analyzing this trajectory was determined. The best that could be done is to use a higher coefficient of drag in a calculation like that in Case 1. (The higher drag coefficient is a result of the twist in the blade.) The higher drag coefficient would decrease the distance traveled by the blade. Thus, there was no point in trying to estimate a higher drag coefficient for Case 2, and thus calculate a less conservative result.

Case 3. The blade is thrown from the WTG in such a manner that it rotates about its center of mass, producing thrust like a helicopter rotor. Lift, drag, and gravity are included in the analysis.

Cases 1 and 3 are analyzed for blade failure speeds of 40, 55, and 75 rpm. The techniques for estimating the trajectories of fragments from explosions[56] are employed.

The maximum ranges, impact velocity, and impact angles are summarized in Table 6.8-1. As indicated by the table, at the expected 55 rpm blade failure speed, the maximum range of the thrown blade is 192 m (630 ft). This compares favorably with the maximum range computed in a vacuum at the optimum throw angle.

Estimates of blade ricochet off the ground and penetration of steel plate on impact were also made. For maximum range trajectories, blade impact occurs at about 50° incidence, and no ricochet is expected. The maximum thickness of mild steel plate which would be penetrated by the blade striking end-on is approximately 0.6 inch (1.5 cm).

TABLE 6.8-1
RESULTS OF BLADE FAILURE ANALYSIS

RPM at Failure	40	55	75
Case 1			
Maximum Range (m)	115	190	326
Impact Velocity (m/s)	41	48	59
Impact Angle (°)	-54	-51	-49
Case 3			
Maximum Range (m)	115	192	330
Impact Velocity (m/s)	41	49	61
Impact Angle (°)	-52	-49	-48

6.9 CONCLUSIONS

The MOD-OA wind turbine generator at Clayton does not impose any appreciable risks to the general public, operating personnel, or equipment and facilities. This conclusion was drawn by identifying the equipment, functions, and operations that potentially could result in hazards, by assessing those hazards for impact and probability, by instituting methods that eliminated hazards or reduced them to an acceptable risk level, and by verifying measures in the design, operating controls, and procedures for installation, test, and maintenance.

The safety design criteria was that no major damage should occur during the service life of the machine because of a single-point failure or a single failure following an undetected failure. The "fail safe" approach was employed. All major safety related systems were provided with redundant and diverse backup systems.

The only part of the wind turbine generator that does not comply with the above criteria and approach is the blade and its attachment structure. The probability of a blade separation is so small that the risk from this event is acceptably small. The low probability resulted from the analysis of the blade and its mounting, the design verifications of the test program, the inspections and checks of the quality program, the redundancy built into the overspeed shutdown circuits, and the extensive inspection program during operation.

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7.0 FAILURE MODES AND EFFECTS ANALYSIS

7.1 INTRODUCTION

The Failure Modes and Effects Analysis (FMEA) was primarily directed at identifying those critical failure modes that would be hazardous to life or would result in major damage to the system. As a result, the analysis was conducted from the "top down", minimizing the extent of analysis that would lead to trivial conclusions, had the analysis been approached from the "bottom up". For example, a component-by-component analysis of a system was not pursued, once it had been established that all system failures lead to the same, non-critical conclusion. This chapter contains a summary of the results of the FMEA.

7.2 EVALUATION CRITERIA

The criteria used for system evaluation was that no major damage should occur because of a single-point failure or a single failure following an undetected failure.

7.3 TASK APPROACH

The MOD-OA wind turbine generator was broken down into the safety system, high speed (rotor) brake system, pitch control system, supervisory system, electrical system, mechanical drive system and rotor, speed increaser (low speed shaft) slip ring, tower slip ring, yaw drive system, microprocessor system, engineering data system, and structures for this analysis. System descriptions are in Section 2.0.

Each system was approached from the top down, and broken down to successive lower levels where it appeared that the criticality of the failure mode warranted more detailed analysis. These analyses were reviewed by the Wind Energy Project Office and the Failure Modes and Effects Analysis Committee.

7.4 SUMMARY AND CONCLUSIONS

The results of this study have been evaluated and the failure evaluation criteria have been satisfied, except for the blade and its attachment structure. Should a blade separate, the study indicated, no additional failures would propagate.

The probability of a blade separation is acceptably small as discussed in Section 6.0. The analysis of the blade and its mounting, the design verifications of the test program, the inspections and checks of the quality program, the redundancy built into the overspeed shutdown circuits, and the inspection program during operation all combine to assure safe operation.

As a result of the FMEA, several deficiencies were found in the requirements and design of the safety system. To eliminate these deficiencies, the following modifications were made:

1. The rotor brake system was made fail-safe; i.e., on loss of power, the brakes are applied.

2. The following safety items were made to have the sensor, primary device (brake solenoid or pitch change fail-safe solenoids), and interconnecting circuitry within the nacelle so they are not dependent on tower slip rings:

   (a) 45 rpm overspeed
   (b) low speed shaft vertical vibration
   (c) low speed shaft horizontal vibration
   (d) emergency feather pressure
   (e) rotor brake pressure

3. Two independent high yaw error signals will cause a shutdown. One uses the existing yaw control system high error signal; the second compares nacelle position to the meteorological tower 90 ft. (27.4 m) elevation direction sensor.

4. Intrusion alarms for control building and nacelle cause shutdown, audible alarm at control building, and warning on dispatcher's console.

5. The reliability of these systems was maximized as they are primary safety devices. Items with maximized reliability through redundancy, minimum electrical path, quality of components, and periodic verification of system operation are:

   (a) 45 rpm overspeed
   (b) low speed shaft horizontal vibration
   (c) low speed shaft vertical vibration
   (d) emergency feather pressure
   (e) rotor brake pressure
   (f) yaw error signal
   (g) generator overcurrent
   (h) generator reverse power

6. The yaw motor high temperature shutdowns were removed.

8.0 ENGINEERING DATA ACQUISITION

Data for evaluating the operation and performance of the MOD-OA wind turbine is obtained by the data acquisition system. The data system consists of sensors located in the nacelle, the control building, and the meteorological tower; three remote multiplexing units; a mobile data system; and a stand alone instrument recorder. An overall description of the instrumentation and data acquisition system was presented previously in Section 2.11.

8.1 INSTRUMENTATION

The sensors associated with the data acquisition system can be segregated according to their specific locations. Each sensor identification code includes a station identification number and a letter which indicates the parameter sensed by the device. The code letters and corresponding sensed parameters utilized for the MOD-OA wind turbine, as well as the station identification numbers, are as follows:

Code Letter	Sensed Parameter	Station Identification No.	Location
A	Acceleration	1	Blade No. 4
C	Linear Displacement	2	Blade No. 5
D	Angular Displacement	3	Hub
E	Torque	4	Low Speed Shaft
F	Frequency	5	Speed Increaser
L	Limit	6	High Speed Shaft
I	Current	7	Generator
P	Pressure	8	Nacelle
R	Speed	9	Yaw System
S	Strain	10	Hydraulic System
T	Temperature	11	Wind Turbine Tower
V	Volts	12	Switchgear
W	Watts or VARS	13	Load Bank
		14	Meteorological Tower

The outputs of the sensors provide input to three remote multiplexer units where the signals are multiplexed and sent to the mobile data system for processing.

8.1.1 ROTOR

Data acquisition sensors associated with the rotor provide input to remote multiplexing unit (RMU) number one. The rotor sensors monitor moments at several locations on the blades, air spring pressure associated with the pitch control system, rotor shaft torque and bending, and blade pitch angle. Table 8.1-1 illustrates the sensor number, location, function and vendor information for each sensor. Where possible, the sensors are standard, commercial components available as off-the-shelf items. Identification of the sensors is

TABLE 8.1-1: ROTOR SENSORS

Sensor Number	Location	Function	Vendor Information
01S000	Blade No. 4	Flap Moment Strain Gage	Micromeasurements CEA-06-250UW-350
01S002	Blade No. 4	Flap Moment Strain Gage	Micromeasurements CEA-06-250UW-350
01S004	Blade No. 4	Chord Moment Strain Gage	Micromeasurements CEA-06-250UW-350
01S006	Blade No. 4	Chord Moment Strain Gage	Micromeasurements CEA-06-250UW-350
01S008	Blade No. 4	Torsion Moment Strain Gage	Micromeasurements CEA-06-250UW-350
01S010	Blade No. 4	Torsion Moment Strain Gage	Micromeasurements CEA-06-250UW-350
01S012	Blade No. 4	Flap Moment Strain Gage	Micromeasurements CEA-06-250UW-350
01S014	Blade No. 4	Chord Moment Strain Gage	Micromeasurements CEA-06-250UW-350
01S016	Blade No. 4	Torsion Moment Strain Gage	Micromeasurements CEA-06-250UW-350
02S050	Blade No. 5	Flap Moment Strain Gage	Micromeasurements CEA-06-250UW-350
02S052	Blade No. 5	Flap Moment Strain Gage	Micromeasurements CEA-06-250UW-350
02S054	Blade No. 5	Chord Moment Strain Gage	Micromeasurements CEA-06-250UW-350
02S056	Blade No. 5	Chord Moment Strain Gage	Micromeasurements CEA-06-250UW-350
02S058	Blade No. 5	Torsion Moment Strain Gage	Micromeasurements CEA-06-250UW-350
02S060	Blade No. 5	Torsion Moment Strain Gage	Micromeasurements CEA-06-250UW-350
02S062	Blade No. 5	Flap Moment Strain Gage	Micromeasurements CEA-06-250UW-350
02S064	Blade No. 5	Chord Moment Strain Gage	Micromeasurements CEA-06-250UW-350
02S066	Blade No. 5	Torsion Moment Strain Gage	Micromeasurements CEA-06-250UW-350
03P102	Hub	Air Spring Pressure	U-3 Model 151 Pressure Transducer
04E170	Rotor Shaft Cpl. End	Rotor Shaft Torque	Micromeasurements CEA-06-250UW-350
04E172	Rotor Shaft Cpl. End	Rotor Shaft Torque	Micromeasurements CEA-06-250UW-350
04S174	Rotor Shaft Flg. End	Rotor Shaft Bending	Micromeasurements CEA-06-250UW-350
04S176	Rotor Shaft Flg. End	Rotor Shaft Bending	Micromeasurements CEA-06-250UW-350
04S178	Rotor Shaft Flg. End	Rotor Shaft Bending	Micromeasurements CEA-06-250UW-350
04S180	Rotor Shaft Flg. End	Rotor Shaft Bending	Micromeasurements CEA-06-250UW-350
03D100	Hub	Blade Pitch Angle	DuraPot Angular Transducer

illustrated on Sensor Identification List: NASA Dwg. No. CF758978 (W1016F04). Location of the sensors is illustrated on the NASA Sensor Location Drawing Nos. CR758975 and CR758976 (W1015F43). The locations of the blade strain gages are identified in Figures 8.1-1, 8.1-2, and 8.1-3. The sensors are wired to RMU No. one in accordance with the Instrumentation Sensor Wiring List: NASA Dwg. Nos. CF758968, CF758969 and CF758970 (W1016F01). Details of the locations and connections of the sensors on the rotor shaft are provided on NASA Dwg. Nos. CF760506 and CF760520 (W1015F95). Relative loads are monitored by resistance type strain gage bridges.

8.1.2 DRIVE TRAIN

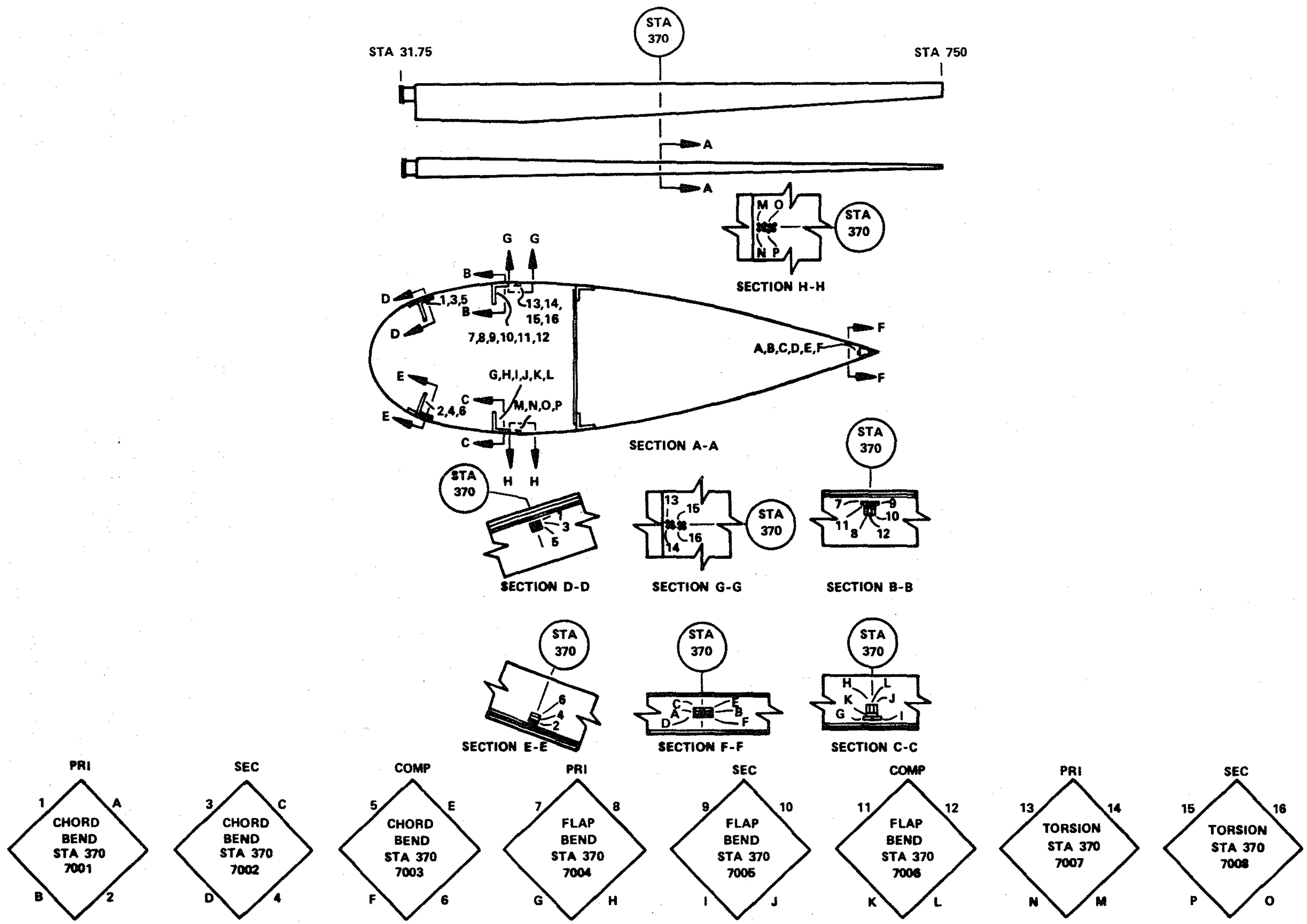
Data acquisition sensors associated with the drive train provide input to remote multiplexing unit number two. The drive train sensors monitor bearing acceleration and temperature, shaft rpm, several drive train temperatures, generator winding temperature, temperature and pressure of the hydraulic system, and generator rpm. Table 8.1-2 illustrates the sensor number, location, function, and vendor information for each sensor. Where possible, the sensors are standard, commercial components available as off-the-shelf items. Identification of the sensors is illustrated on Sensor Identification List NASA Dwg. No. CF758978 (W1016F04). Location of the sensors is illustrated on Sensor Location NASA Dwg. Nos. CR758975 and CR758976 (W1015F43). The sensors are wired to RMU No. two in accordance with Instrumentation Sensors Wiring List NASA Dwg. Nos. CF758968, CF758969 and CF758970 (W1016F01).

8.1.3 NACELLE/BEDPLATE

Data acquisition sensors associated with the nacelle/bedplate provide input to either remote multiplexing unit number two or number three. The nacelle/bedplate sensors monitor brake pad emperature, brake bottle pressure, internal nacelle temperatures, moments of the bedplate, temperatures in the yaw drive system, wind speed, yaw error, and nacelle direction. Table 8.1-3 illustrates the sensor number, location, function, and vendor information for each sensor. Where possible, the sensors are standard, commercial components available as off-the-shelf items: [see Identification List NASA Dwg. No. CF758978 (W1016F04)]. Location of the sensors is illustrated on Sensor Location NASA Dwg. Nos. CR758975 and CR758976 (W1015F43). The sensors are wired to the remote multiplexing units in accordance with Instrumentation Sensor Wiring List NASA Dwg. Nos. CF758968, CF758969 and CF758970 (W1016F01).

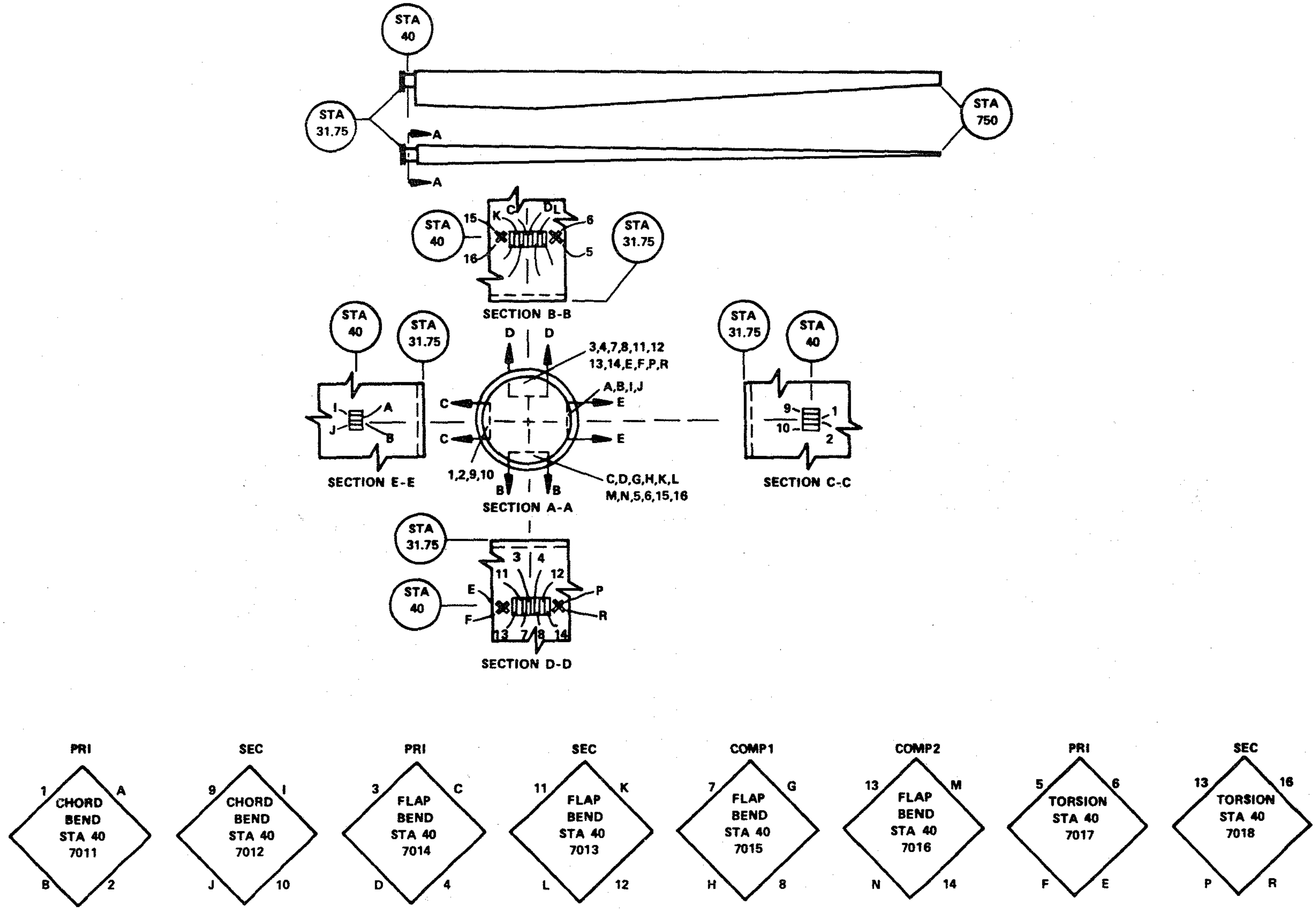
8.1.4 TOWER

Data acquisition sensors associated with the tower provide input to remote multiplexing unit number three. The tower sensors monitor tower top acceleration, hydraulic system pressure, and yaw torque. Table 8.1-4 illustrates the sensor numbers, location, function, and vendor information for each sensor. Where possible, the sensors are standard, commercial components available as off-the-shelf items. Identification of sensors is illustrated on Sensor Identification List NASA Dwg. No. CF758978 (W1016F04). Location of the sensors is illustrated on Sensor Location NASA Dwg. Nos. CR758975 and CR758976 (W1015F43) and NASA Dwg. No. CF759025 (W1016F10). The sensors are wired to the



NOTE: FOR CHORD AND FLAP BENDING USE CEA-13-250UW-350 OR EQUIV STRAIN GAGES
FOR TORSION USE FABX-25-35-313 OR EQUIV STRAIN GAGES

Figure 8.1-1. MOD-0A Blade Strain Gage Locations



NOTE: FOR CHORD AND FLAP BENDING USE CEA-06-250UW-380 OR EQUIV STRAIN GAGES FOR TORSION USE FABX-25-35-56 OR EQUIV STRAIN GAGES

Figure 8.1-2. MOD-0A Blade Strain Gage Locations

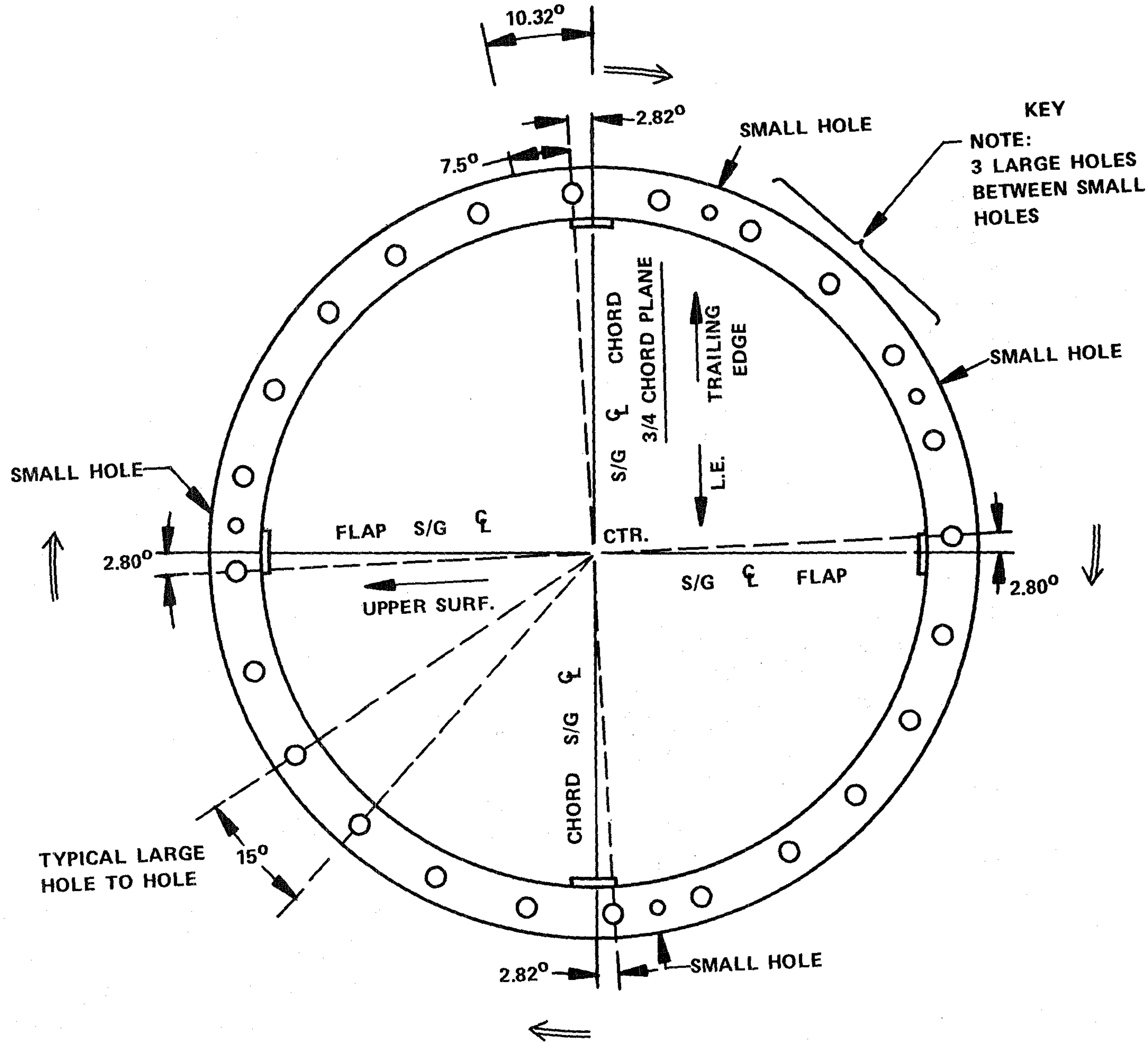
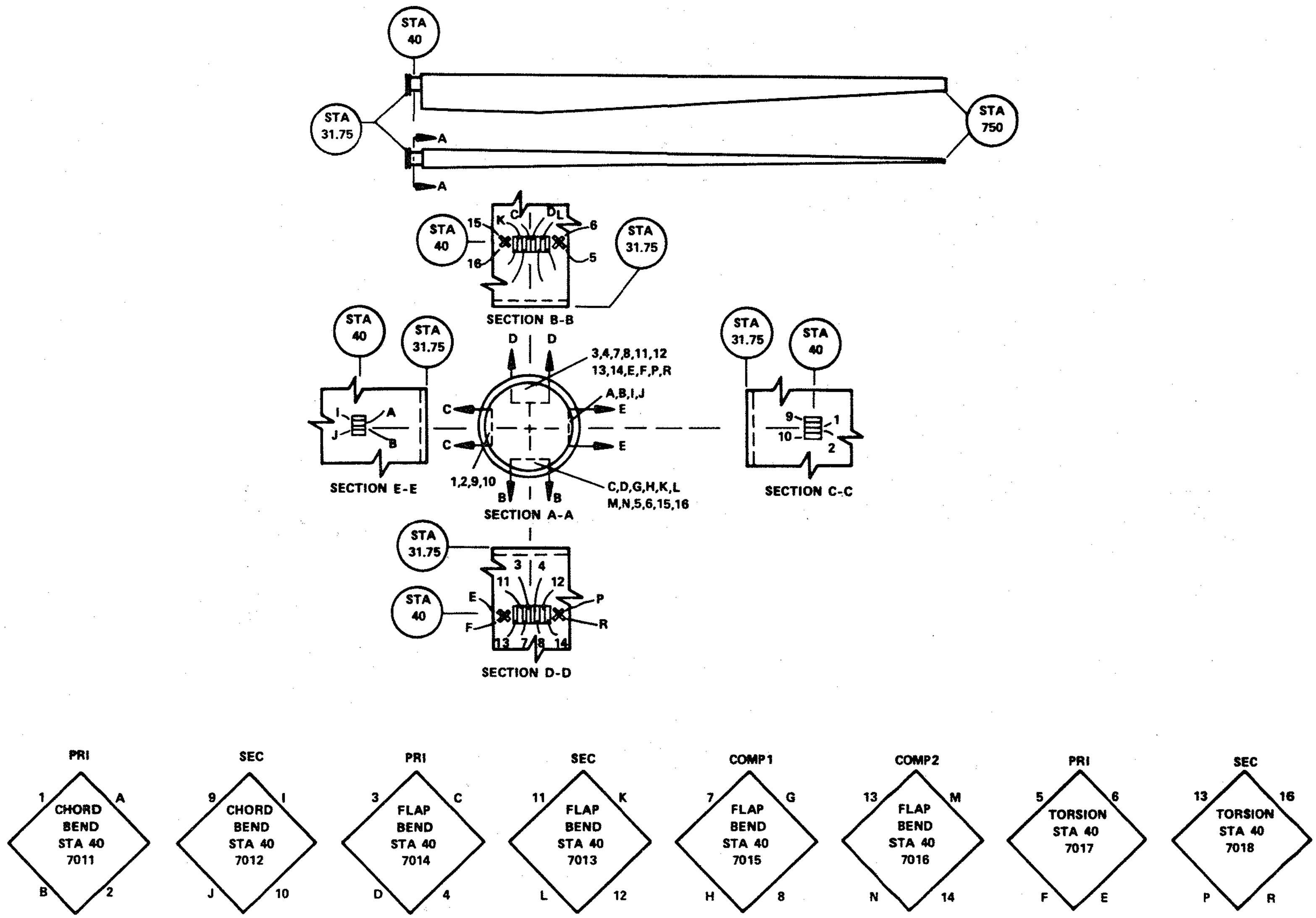


Figure 8.1-3. MOD-OA Blade Strain Gage Locations - Reference Centerlines



NOTE: FOR CHORD AND FLAP BENDING USE CEA-06-250UW-380 OR EQUIV STRAIN GAGES FOR TORSION USE FABX-25-35-56 OR EQUIV STRAIN GAGES

Figure 8.1-2. MOD-OA Blade Strain Gage Locations

TABLE 8.1-3: NACELLE/BEDPLATE SENSORS

Sensor Number	Location	Function	Vendor Information
06T250	Brake Pad	Pad Temperature	Type T (Cu/Con) Thermocouple
06P258	Brake Bottle	Pressure	CGI 201-9
08T350	Nacelle	Forward Temperature	Type T (Cu/Con) Thermocouple
08T352	Nacelle	Rear Temperature	Type T (Cu/Con) Thermocouple
08S358	Top of Bedplate	Bed Plate Moment.	Micromeasurements CEA-06-250UW-350
08S360	Bottom of Bedplate	Bedplate Moment	Micromeasurements CEA-06-250UW-350
09T400	Yaw Motor A	Temperature	Type T (Cu/Con) Thermocouple
09T402	Yaw Motor B	Temperature	Type T (Cu/Con) Thermocouple
08R354	Top of Nacelle.	Wind Speed.	Aerovane Model 120
08D356	Top of Nacelle	Yaw Error	Aerovane Model 120
09R404	Yaw Drive System. . . .	Yaw CW ON	
09R406	Yaw Drive System	Yaw CCW ON	
11D500	Base of Tower Slip. . . Ring	Nacelle Direction	

TABLE 8.1-4: TOWER SENSORS

Sensor Number	Location	Function	Vendor Information
09E408	Yaw Shaft #1.	Yaw Torque.	Lebow Assoc. Model 6901
09E410	Yaw Shaft #2	Yaw Torque	Lebow Assoc. Model 6901
11A502	Top of Tower.	Tower Top X Acceleration . . .	Sundstrand Model QA-1100
11A504	Top of Tower	Tower Top Y Acceleration	Sundstrand Model QA-1100
11A506	Top of Tower.	Tower Top X Acceleration . . .	Sundstrand Model QA-1100
11A508	Top of Tower	Tower Top Y Acceleration	Sundstrand Model QA-1100
11P510	Yaw Hydraulic Panel . .	Hydraulic Oil Pressure. . . .	CGI 201-9

remote multiplexing unit in accordance with Instrumentation Sensor Wiring List: NASA Dwg. Nos. CF758968, CF758969, and CF758970 (W1016F01). Since the yaw torque requires the transducer to be in a rotating system, a Lebow transformer is used to transfer the excitation voltage from the stationary to the rotating member and the output voltage from the rotating member back to the stationary member.

8.1.5 CONTROL BUILDING (SWITCHGEAR)

Data acquisition sensors associated with the control building are located in the switchgear and provide input to remote multiplexing unit number three. These sensors monitor generator phase voltages, phase currents, output power, output VARs, and frequency. Table 8.1-5 illustrates the sensor number, location, function, and vendor information for each sensor. The sensors are standard commercial components available as off-the-shelf items. Identification of sensors is illustrated on Sensor Identification List NASA Dwg. No. CF758978 (W1016F04). The sensors are wired to the RMU in accordance with Instrumentation Sensor Wiring List NASA Dwg. Nos. CF758968, CF758969, and CF758970 (W1016F01). As shown on NASA Dwg. Nos. CF759035, CF759036, CF759037, CF759038, and CF759039 (W1016F20), some of the switchgear sensors also provide input to the amplifier panel associated with the microprocessor.

The control building houses the control panel for the wind turbine system which includes signal conditioning devices for the strain gages associated with the measurement of yaw torque. Two Daytronic model 9178A strain gage signal conditioners convert the input received from the strain gages and outputs standard five volt data signals which are displayed on panel meters in the control building for operator use.

8.1.6 METEOROLOGICAL TOWER

Data acquisition sensors associated with the meteorological tower are located at the 30, 100, and 150 foot (9.14, 30.48, and 45.72 m) elevations and provide input to remote multiplexing unit number three. The meteorological tower sensors consitute a wind measurement system which consists of three MRI* 1074-6 wind sensors and signal conditioning circuits.

Wind direction and wind speed are measured with the MRI 1074-6 sensor. The unit is a combined cup and vane sensor. Three conical aluminum anemometer cups are located directly above the azimuth vane. The anemometer shaft drives a tachometer generator which provides a generator output voltage proportional to wind speed.

Wind direction is obtained with a single-blade aluminum tail vane which incorporates a nose damping vane with static balance. The 360° azimuth transducer provides a resistance proportional to the wind angle.

* MRI - Meteorological Research Inc.

TABLE 8.1-5: SWITCHGEAR SENSORS

Sensor Number	Location	Function	Vendor Information
12V550	Switchgear	Generator A Phase Voltage	Scientific Columbus VT-110AZ
12V552	Switchgear	Generator B Phase Voltage	Scientific Columbus VT-110AZ
12V554	Switchgear	Generator C Phase Voltage	Scientific Columbus VT-110AZ
12I556	Switchgear	Generator A Phase Current	Scientific Columbus CT-510AZ
12I558	Switchgear	Generator B Phase Current	Scientific Columbus CT-510AZ
12I560	Switchgear	Generator C Phase Current	Scientific Columbus CT-510AZ
12I562	Switchgear	Generator Field Current	10A, 50MV Shunt
12W564	Switchgear	Generator Output Power	Scientific Columbus WT34-2K5A4
12W566	Switchgear	Generator Output VARS	Scientific Columbus VT34-2K5A4
12F568	Switchgear	Frequency	Scientific Columbus 6284A

TABLE 8.1-6: METEROLOGICAL TOWER SENSORS

Sensor Number	Location	Function	Vendor Information*
14R600	30 Ft. (9.14 m) Level	Wind Speed	MRI 1074-6 Wind Sensor
14R602	100 Ft. (30.48 m) Level	Wind Speed	MRI 1074-6 Wind Sensor
14R604	150 Ft. (45.72 m) Level	Wind Speed	MRI 1074-6 Wind Sensor
14D606	30 Ft. (9.14 m) Level	Wind Direction	MRI 1074-6 Wind Sensor
14D608	100 Ft. (30.48 m) Level	Wind Direction	MRI 1074-6 Wind Sensor
14D610	150 Ft. (45.72 m) Level	Wind Direction	MRI 1074-6 Wind Sensor
14T612	Meteorological Tower	Ambient Temperature	

* MRI - METEORLOGICAL RESEARCH INC.

Outputs from the wind speed and wind direction transducers provide input to signal conditioning equipment which outputs 0-5 Vdc signals proportional to wind speed and direction. Table 8.1-6 illustrates the sensor number, location, function, and vendor information for each sensor. Identification of sensors is illustrated on Sensor Identification List NASA Dwg. No. CF758978 (W1016F04). The sensors are wired to RMU number three in accordance with Instrumentation Sensor Wiring List: NASA Dwg. Nos. CF758968, CF758969 and CF758970 (W1016F01).

8.2 REMOTE MULTIPLEXER UNITS

Remote Multiplexer Units (RMUs) for the MOD-OA wind turbine are located on the hub, on the bedplate, and in the control building. Each RMU contains the necessary electronics for signal conditioning and multiplexing data signals onto two coaxial cables for transmission to the mobile data system.

Each RMU is enclosed in an aluminum case designed to protect the interior electronic components from water or dust by meeting NEMA 12 standards. The hinged access door has a gasketed seal and all electrical connections to the interior of the RMU are made with MS weatherproof connectors. Each RMU is designed to operate over a temperature range of -35°C to +55°C, humidity range from 0 to 100 percent, and a vibration range of ± 15 G's along any axis. Figure 8.2-1 shows RMU number two which is located on the bedplate.

Each RMU can accommodate up to 32 data channels with each channel having a four pole, low pass active Butterworth filter providing a bandwidth of 40 Hz and adjustable measurement ranges. All channels can be individually configured to signal condition data from either sensors with resistance outputs, such as strain gages, or sensors with voltage outputs. Twenty of the 32 channels have additional capability to signal condition data from copper/constantan thermocouples.

Each conditioned data channel is frequency modulated onto a center frequency and summed with other modulated channels into one of two frequency modulated multiplexes of sixteen channels each. The center frequencies are spaced 500 Hz apart, from 1000 Hz to 8500 Hz, and each data channel will produce a center frequency deviation of ± 125 Hz. A reference frequency is also summed into each multiplex for use when the data is processed. The multiplex summing amplifiers are capable of transmitting the multiplex data over 2000 feet (609.6 m) of coaxial cable to the mobile data system. Additional details of the Remote Multiplexer Units have been documented.[57]

8.2.1 HUB RMU

Table 8.2-1 illustrates the sensor numbers having input to RMU Number One located on the hub. The table also provides the multiplex channel, parameter, and location associated with each sensor.

8.2.2 BEDPLATE RMU

Table 8.2-2 illustrates the sensor numbers having input to RMU Number Two

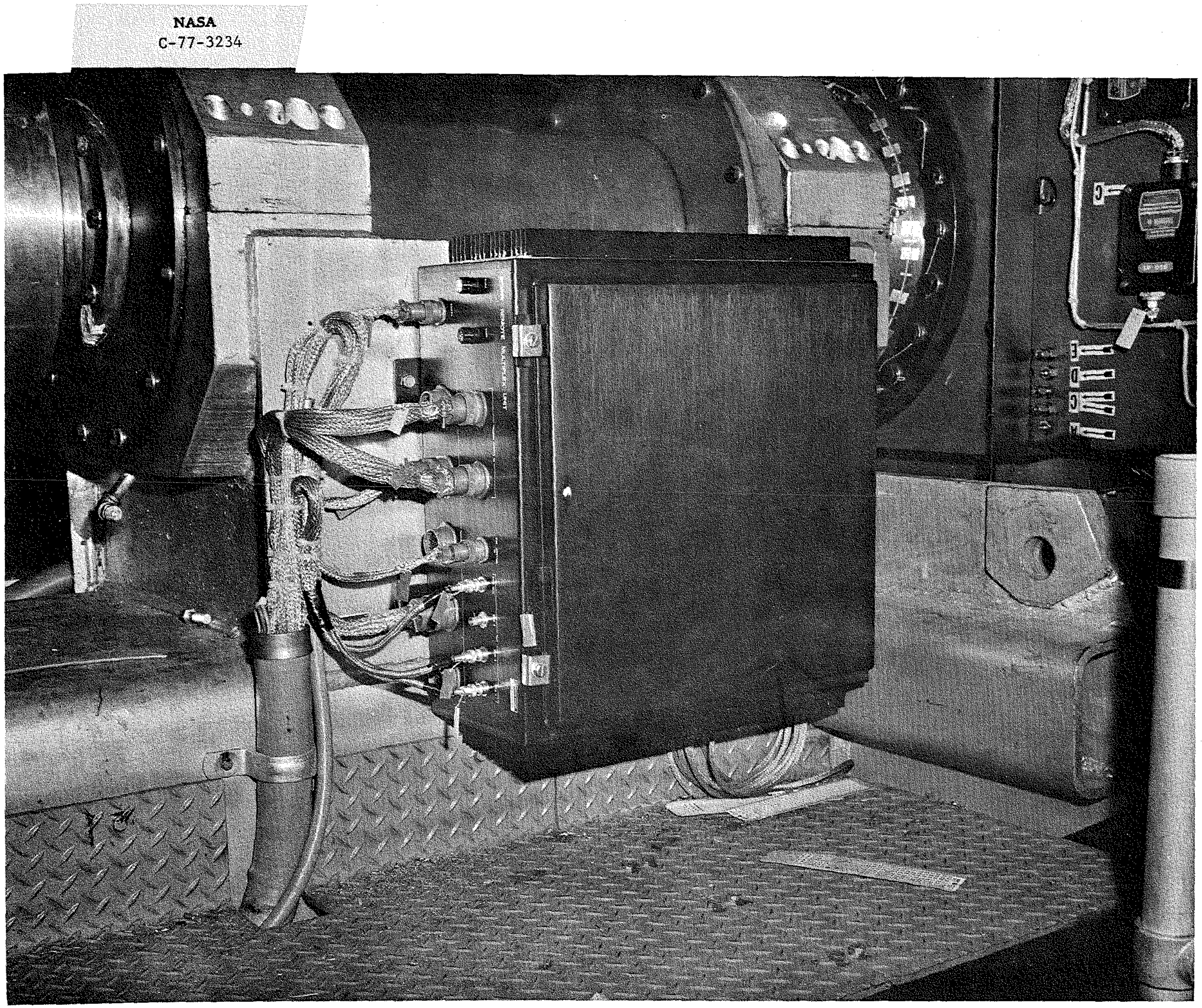


Figure 8.2-1. MOD-OA Remote Multiplexer Unit Number Two

TABLE 8.2-1: RMU NUMBER ONE LOCATED ON THE HUB

SENSOR NUMBER	FM MULTIPLEX CHANNEL	SENSED PARAMETER	LOCATION
01S000	Ch A-00	Strain Gage	Blade #4
01S002	Ch A-01	Strain Gage	Blade #4
01S004	Ch A-02	Strain Gage	Blade #4
01S006	Ch A-03	Strain Gage	Blade #4
01S008	Ch A-04	Strain Gage	Blade #4
01S010	Ch A-05	Strain Gage	Blade #4
01S012	Ch A-06	Strain Gage	Blade #4
01S014	Ch A-07	Strain Gage	Blade #4
01S016	Ch A-08	Strain Gage	Blade #4
02S050	Ch B-00	Strain Gage	Blade #5
02S052	Ch B-01	Strain Gage	Blade #5
02S054	Ch B-02	Strain Gage	Blade #5
02S056	Ch B-03	Strain Gage	Blade #5
02S058	Ch B-04	Strain Gage	Blade #5
02S060	Ch B-05	Strain Gage	Blade #5
02S062	Ch B-06	Strain Gage	Blade #5
02S064	Ch B-07	Strain Gage	Blade #5
02S066	Ch B-08	Strain Gage	Blade #5
03P102	Ch B-09	Air Spring Pressure	Hub
04E170	Ch A-10	Rotor Shaft Torque	Rotor Shaft Coupling End
04E172	Ch A-11	Rotor Shaft Torque.	Rotor Shaft Coupling End
04S174	Ch A-12	Rotor Shaft Bending	Rotor Shaft Flange End
04S176	Ch A-13	Rotor Shaft Bending	Rotor Shaft Flange End
04S178	Ch A-14	Rotor Shaft Bending	Rotor Shaft Flange End
04S180	Ch A-15	Rotor Shaft Bending	Rotor Shaft Flange End

TABLE 8.2-2: RMU NUMBER TWO LOCATED ON THE BEDPLATE

SENSOR NUMBER	FM MULTIPLEX CHANNEL	SENSED PARAMETER	LOCATION
04A150 . .	Ch A-09 . . .	Bearing "A" Vertical Acceleration	Bearing A
04A152 . .	Ch A-10 . . .	Bearing "B" Vertical Acceleration	Bearing B
04A154 . .	Ch A-11 . . .	Bearing "B" Horizontal Acceleration	Bearing B
04A156 . .	Ch B-10 . . .	Bearing "B" Horizontal Acceleration	Bearing B
04T158 . .	Ch A-00 . . .	Bearing "A" Temperature.	Bearing A
04T160	Ch A-01	Bearing "B" Temperature	Bearing B
04D162 . .	Ch A-08 . . .	Main Shaft RPM	Low Speed Shaft
04D166	Ch B-11	Low Speed Shaft Angular Position	Low Speed Shaft
04T182 . .	Ch B-00 . . .	Temperature.	Hyd. Rotary Coupling
05T200	Ch A-02	Oil Temperature	Speed Increaser
05T202 . .	Ch B-04 . . .	Temperature.	Front Bearing Plate
05T204	Ch B-05	Temperature	Rear Bearing Plate
05T206 . .	Ch B-08 . . .	Temperature.	Front Bearing Plate
05T208	Ch B-09	Temperature	Rear Bearing Plate
06T250 . .	Ch A-03 . . .	Temperature.	Brake Pad
06T252	Ch A-04	Pillow Block Bearing Temperature	Pillow Block
06A254 . .	Ch A-12 . . .	Pillow Block Bearing Horizontal. Acceleration .	Pillow Block
06P258 . .	Ch A-13 . . .	Brake Bottle Pressure.	Brake Bottle
07T300	Ch A-05	Winding Temperature	Generator
08T350 . .	Ch B-01 . . .	Nacelle Forward Temperature. . . .	Nacelle
08T352	Ch A-06	Nacelle Rear Temperature	Nacelle
08S358 . .	Ch A-14 . . .	Bedplate Moment.	Top of Bedplate
08S360	Ch B-12	Bedplate Moment	Bottom of Bedplate
09T400 . .	Ch B-02 . . .	Temperature.	Yaw Drive System
09T402	Ch B-03	Temperature	Yaw Drive System
10P450 . .	Ch A-15 . . .	Hydraulic Oil Pressure	Hydraulic System
10T452	Ch B-06	Hydraulic Oil Temperature	Hydraulic System
10T454 . .	Ch A-07 . . .	Hydraulic Oil Temperature.	Hydraulic System

located on the bedplate. The table also provides the multiplex channel, parameter, and location associated with each sensor.

8.2.3 CONTROL BUILDING RMU

Table 8.2-3 illustrates the sensor numbers having input to RMU Number Three located in the control building. The table also provides the multiplex channel, parameter, and location associated with each sensor.

8.3 MOBILE DATA SYSTEM

The Mobile Data System shown in Figure 8.3-1 contains the necessary equipment for processing data at a wind turbine site. This instrument vehicle is self-propelled and constructed to permit movement from site to site over public highways without special permits or approvals. The vehicle is outfitted with an air ride suspension on both front and rear axles to limit road-induced vibration and shock to the data processing equipment. Two heating and cooling units installed on the rear of the mobile data system maintain the interior temperature at a nominal 70°F (21°C) over an exterior temperature range of -20°F to 120°F (-28°C to 50°C). An overview of the flow of data within the mobile data system was shown previously in Figure 2.11-1.

The six frequency modulated multiplexes, two for each RMU, enter the mobile data system and are connected to the input patch panel in the analog processing cabinet (Figures 8.3-2 and 8.3-3). Each multiplex can be patched to one track of a fourteen-track tape recorder/reproducer and simultaneously patched to a group of frequency modulation discriminators. The analog tape recorder operates at a speed of 15/16 in/s (0.024 m/s) and records all six multiplexes plus IRIG B time signal for data playback at a later time. A discriminator is provided for each multiplex and the output of each discriminator is connected to the output patch panel.

From the output patch panel, each electrical analog can be patched to one of sixteen strip chart recorder channels, a spectrum analyzer, or an analog digital converter. The strip chart recorders provide real time monitoring of high frequency data. The spectrum analyzer computes the frequency spectrum of an input signal over the frequency range of 0.1 to 25.6 Hz in 0.1 Hz steps. The analog to digital converter samples an input signal and converts the sample to a twelve bit binary word with a conversion rate of 25 kHz for entry into the digital processing cabinets (Figure 8.3-3).

Each converted binary word is passed from the converter to a data compressor for testing against as many as three predefined algorithms. If the binary word passes the algorithm test, the word is passed to a digital computer for further processing. If the word fails to pass the test, the word is not passed and algorithm testing on the next binary word begins. Algorithms available for use include pass if within a plus or minus limit, pass if outside a plus or minus limit, pass if the magnitude has changed by more than a specified value from the last passed binary word, and pass every N^{th} word where N can be any value between 0 and 8000. By proper selection of the algorithms, the amount of data

TABLE 8.2-3: RMU NUMBER THREE LOCATED IN THE CONTROL BUILDING

SENSOR NUMBER	FM MULTIPLEX CHANNEL	SENSED PARAMETER	LOCATION
03D100	Ch A-00	Blade Pitch Angle	Hub
07R302	Ch A-01	Generator RPM	Generator
07R304	Ch B-00	Generator RPM	Generator
08R354	Ch A-02	Wind Speed	Aerovane
08D356	Ch A-03	Nacelle Yaw Error	Aerovane
09R404	Ch A-04	Yaw CW ON	Yaw Drive System
09R406	Ch A-05	Yaw CCW ON	Yaw Drive System
09E408	Ch A-06	Yaw Torque	Yaw Shaft #1
09E410	Ch A-07	Yaw Torque	Yaw Shaft #2
11D500	Ch A-08	Nacelle Direction	Base of Tower Slip Ring
11A502	Ch A-09	Tower Top Acceleration	Top of Tower
11A504	Ch A-10	Tower Top Acceleration	Top of Tower
11A506	Ch B-14	Tower Top Acceleration	Top of Tower
11A508	Ch B-15	Tower Top Acceleration	Top of Tower
11P510	Ch B-13	Hydraulic Oil Pressure	Yaw Hydraulic Panel
12V550	Ch A-11	Generator A Phase Voltage	Switchgear
12V552	Ch B-01	Generator B Phase Voltage	Switchgear
12V554	Ch B-02	Generator C Phase Voltage	Switchgear
12I556	Ch A-12	Generator A Phase Current	Switchgear
12I558	Ch B-03	Generator B Phase Current	Switchgear
12I560	Ch B-04	Generator C Phase Current	Switchgear
12I562	Ch B-05	Generator Field Current	Switchgear
12W564	Ch A-13	Generator Output Power	Switchgear
12W566	Ch A-14	Generator Output VARS	Switchgear
12F568	Ch B-06	Frequency	Switchgear
14R600	Ch B-07	Wind Speed at 30 Ft. (9.14 m)	Meteorological Tower
14R602	Ch B-08	Wind Speed at 100 Ft.(30.48 m)	Meteorological Tower
14R604	Ch B-09	Wind Speed at 150 Ft.(45.72 m)	Meteorological Tower
14D606	Ch B-10	Wind Direction at 30 Ft. (9.14 m)	Meteorological Tower
14D608	Ch B-11	Wind Direction at 100 Ft. (30.48 m)	Meteorological Tower
14D610	Ch B-12	Wind Direction at 150 Ft. (45.72 m)	Meteorological Tower
14T612	Ch A-15	Ambient Temperature	Meteorological Tower

C-77-3057

Figure 8.3-1. Mobile Data System

NASA
C-77-3058

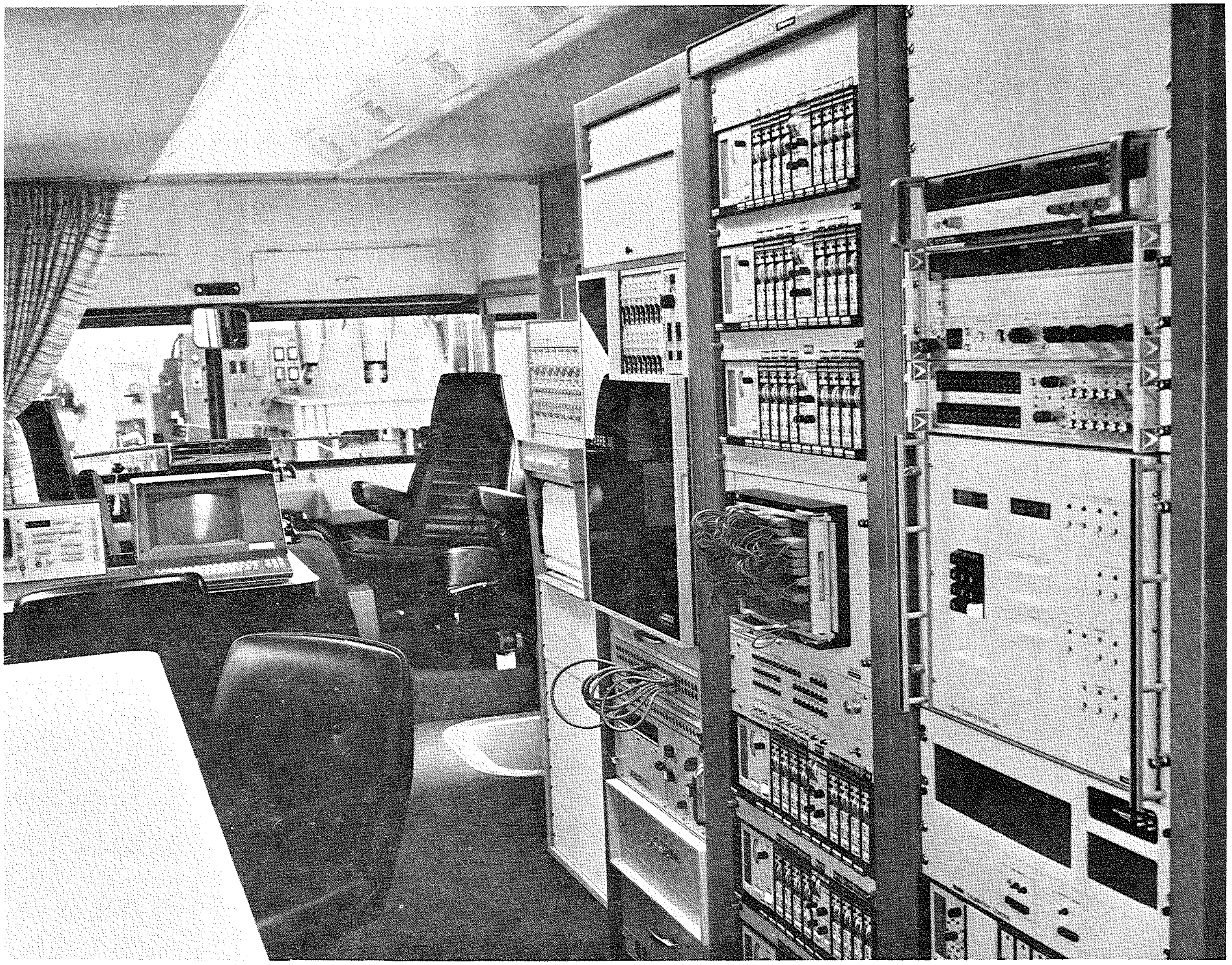


Figure 8.3-2. Interior of Mobile Data System (Looking Forward)

NASA
C-77-3056

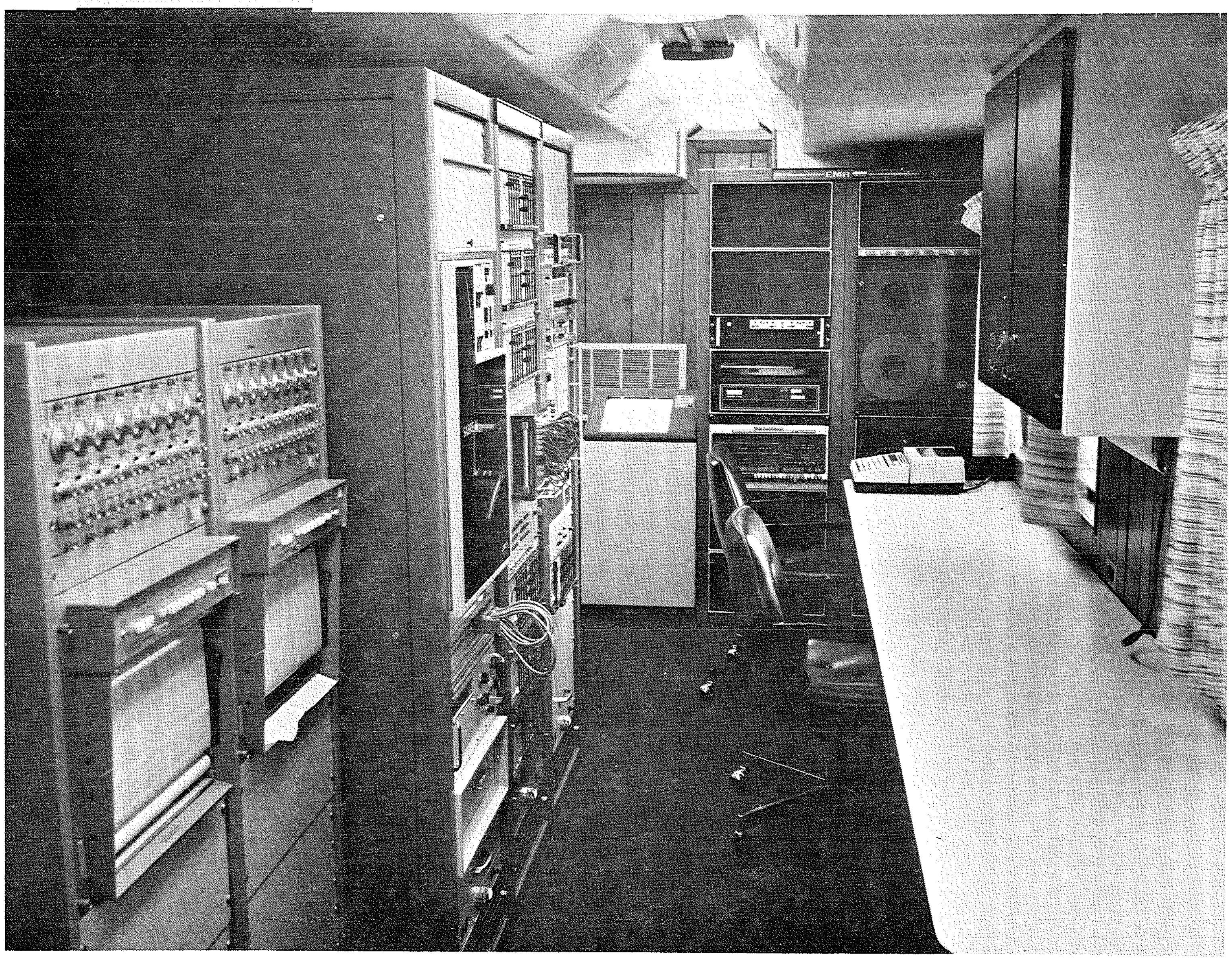


Figure 8.3-3. Interior of Mobile Data System (Looking Aft)

requiring further processing can be reduced and still achieve the data requirements for accuracy.

The digital computer that receives the passed binary words performs two functions with the words. If selected by the PIV operator, the binary words representing samples from a specific data channel are converted to engineering units (e.g., degrees C) and displayed in real time on a CRT. Up to 20 data channels can be converted and displayed at the same time. In addition, all binary words received from the compressor are recorded on digital magnetic tape. Time of the year is also recorded on the digital tape to aid in retrieving data from the tape at a later time. The digital tape is the official data record of the wind turbine and is premanently stored for future study and analysis.

Data recorded on digital tape can be retrieved by the digital processing system and plotted versus time. The mobile data system operator specifies the parameter to be plotted and the time over which the plot is to be made. The digital processing system then reaches the magnetic tape and generates a plot. The flow of data for the data system is shown in Figure 2.11-1. Additional details of the mobile data system have been documented.[57]

8.4 STAND ALONE INSTRUMENT RECORDER

The Stand Alone Instrument Recorder (SAIR) was provided initially to record data when the mobile data system was no longer at the site. The SAIR provided for continuous, 24 hours per day, recording of four tracks of data. Three data tracks supported the three FM multiplex signals transmitted by the remote multiplexer units. The fourth track supported an internally generated IRIGB, time of day, time code signal. The tape consisted of a continuous loop which provided a stored record of the previous thirty minutes of data. Full tape erasure was provided for immediately prior to recording the most current data.

The SAIR was capable of continuous, uninterrupted operation until a remote stop command was initiated. Reception of a remote stop command inhibited further operation until a local reset command was given.

The time base of the time of day code generator was derived from an internal crystal controlled oscillator. Six thumbwheel switches and one time reset pushbutton provided the capability of entering a given time of day into the system. The time code generator automatically started at zero upon reapplication of power to the SAIR after a power interruption. A reproduce head and preamplifier were provided to allow for system checkout. The SAIR was a L'Garde Products model 20366 recorder.

The data recorded by the SAIR included those sensors identified on Table 8.4-1.

TABLE 8.4-1: SAIR DATA TAPE CHANNELS

SENSOR NUMBER	FUNCTION	UNITS
01S000	Flap Moment Station 40	Ft-lbs
01S004	Chord Moment Station 40	Ft-lbs
02S052	Flap Moment Station 40	Ft-lbs
02S056	Chord Moment Station 40	Ft-lbs
01S012	Flap Moment Station 370	Ft-lbs
01S014	Flap Moment Station 370	Ft-lbs
03D100	Blade Pitch Angle	Degrees
03P102	Air Spring Pressure	PSIG
04A152	Bearing B Vertical Acceleration Y	G's
04A154	Bearing B Horizontal Acceleration Z	G's
04A156	Bearing B Horizontal Acceleration X	G's
04T158	Bearing A Temperature	°F
04T160	Bearing B Temperature	°F
04D162	Low Speed Shaft Home Position	--
04S170	Rotor Torque	Ft-lbs
04S174	Shaft Bending, 0 Degrees	Ft-lbs
04S178	Shaft Bending, 90 Degrees	Ft-lbs
05T200	Speed Increaser Oil Temperature	°F
06T252	Pillow Block Bearing Temperature	°F
06P258	Brake Bottle Pressure	PSIG
07T300	Generator Winding Temperature	°F
07R302	Generator Rotational Speed	RPM
08T352	Nacelle Rear Temperature	°F
08R354	Wind Speed	MPH
08D356	Yaw Error	Degrees
08S358	Bedplate Moment	Ft-lbs
09E408	Yaw Torque	In-lbs
09E410	Yaw Torque	In-lbs
10P450	Hydraulic Oil Pressure	PSIG
10T454	Hydraulic Oil Temperature	°F
11D500	Nacelle Direction	Degrees
11A502	Tower X Acceleration Point A	G's
11A504	Tower Y Acceleration Point A	G's
11A506	Tower X Acceleration Point B	G's
12V550	Generator Output Voltage Phase A	Volts RMS
12I556	Generator Output Current Phase A	Amps RMS
12W564	Generator Output Power	kW
12W566	Generator Output VARS	kVARS
14R600	Wind Velocity, 30 Feet (9.14 m)	MPH
14R602	Wind Velocity, 100 Feet (30.38 m)	MPH
14R604	Wind Velocity, 150 Feet (45.72 m)	MPH
14D608	Wind Direction, 100 Feet (30.38 m)	Degrees
14T612	Air Temperature	°F

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9.0 INITIAL OPERATING PERFORMANCE

First rotation of the Clayton MOD-OA wind turbine generator was accomplished on November 30, 1977. In January 1978, the machine completed its first 100 hours of operation, and in March 1978, the wind turbine was released for utility operation. The following sections document the operational experience gained in the initial four months of operation from November 30, 1977 through March 1978.

9.1 AERODYNAMIC PERFORMANCE

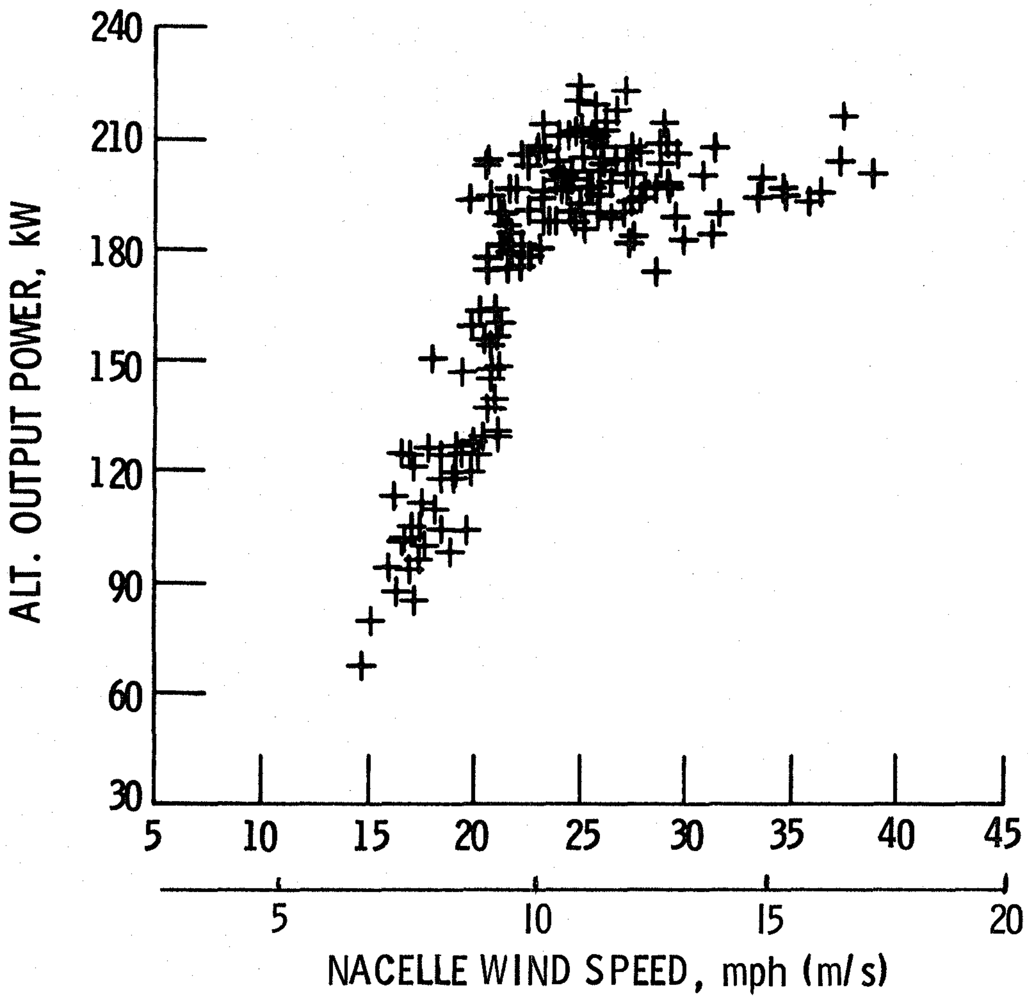
Of primary importance in the design of any wind turbine is the accurate prediction of the machine's performance characteristics. Data from the Clayton wind turbine have been analyzed to enable correlation of the predicted and actual performance. This section contains results of this analysis for alternator power output and drive train performance. Power oscillations data are also presented.

9.1.1 MEASURED POWER VERSUS WIND SPEED

The performance predictions for the MOD-OA wind turbine were calculated using an aerodynamic performance code PROP. This analysis is based on the blade element/momentum theory of rotor performance.[58] Details of the MOD-OA blade geometry are given in Sections 2.4 and 4.1.

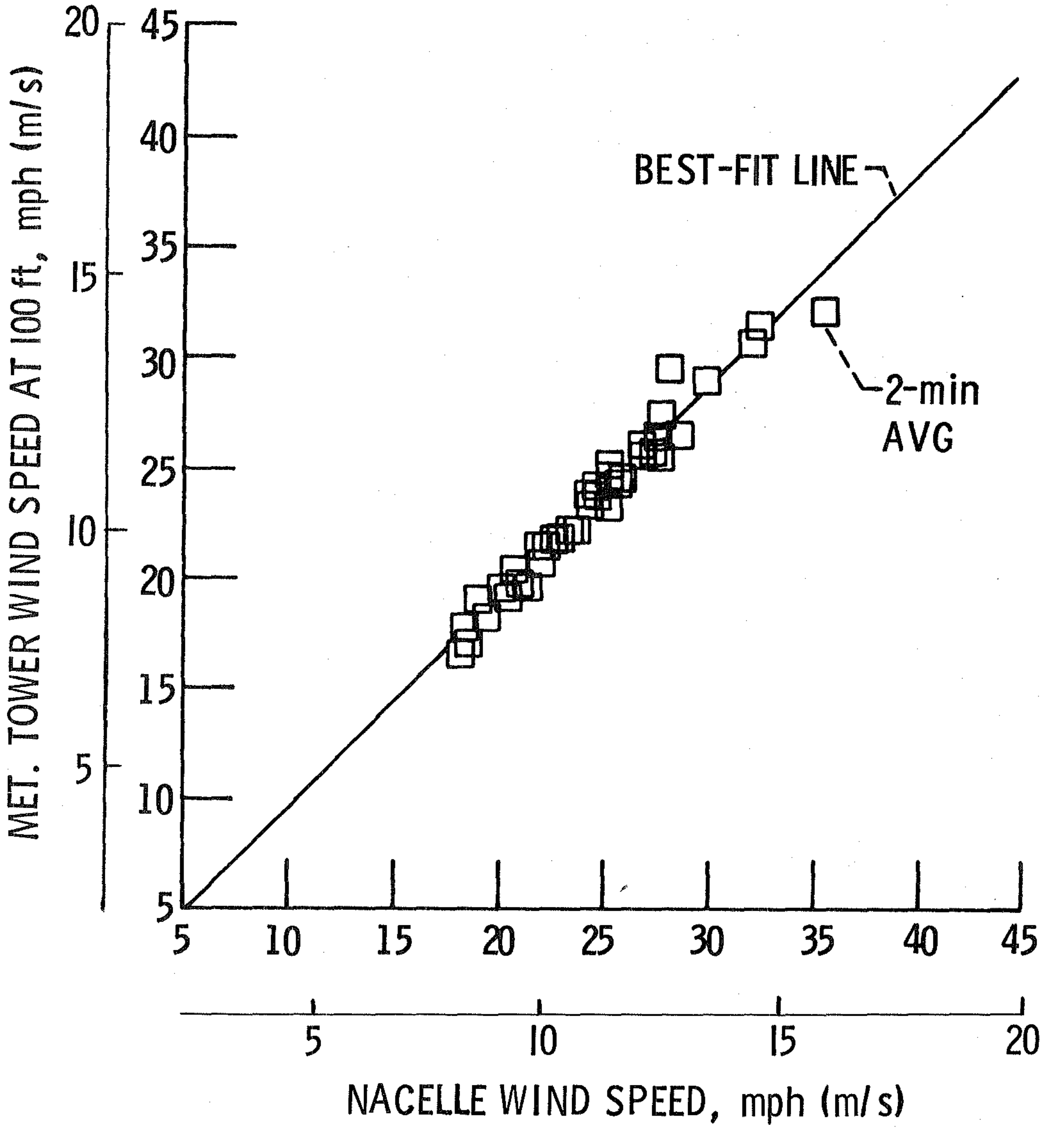
The process of correlating wind turbine performance with wind measurements was not completely straightforward. Two problems were encountered in making the correlation. First, wind measurements must be made close enough to the wind turbine to be representative of the "same" wind that drives the rotor, but far enough away to eliminate any interference effects. Second, an anemometer registers a wind value at a point, while the turbine responds to the wind that engulfs the entire disk swept by the blade.

The approach taken to reduce these problems was: (1) To provide a wind measurement as close to the rotor as possible, the average alternator power for each revolution of the rotor was correlated with the simultaneous measurement of nacelle wind speed. Figure 9.1.1-1 shows a sampling (1/20th) of 1-1/2 hours of data analyzed. (2) To eliminate the interference effects of their rotor and nacelle on the nacelle wind measurements, the 2-minute averages of wind speeds at the nacelle and meteorological tower at 100 feet (30.5 m) were related. This was done by calculating the least squares best-fit straight line to the data. Two-minute averaging was chosen based on calculations of spectral content of the wind and results reported elsewhere (See Reference 59). This data and the curve fit are shown in Figure 9.1.1-2. The wind measurements in the power-versus-nacelle wind relation were then rescaled, using the equation of this best-fit line. The final result of alternator power versus free-stream wind speed is shown in Figures 9.1.1-3 (a) and (b). Figure 9.1.1-4 shows the corresponding power coefficient, C_p, versus tip speed ratio



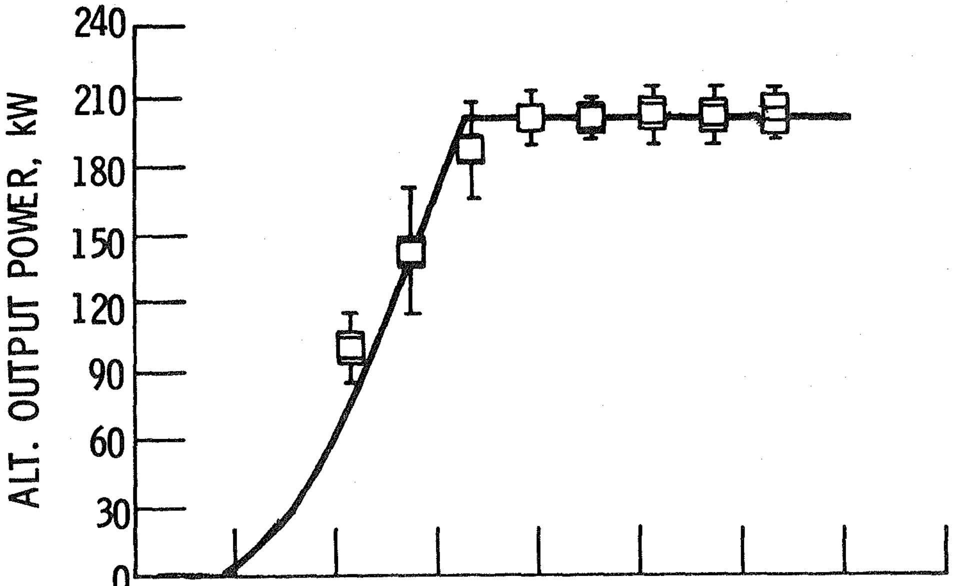
Note: Each Point Represents Simultaneous 1-Revolution (1.5 sec) Averages

Figure 9.1.1-1. Alternator Power Output vs. Wind Speed Measured on the Nacelle.

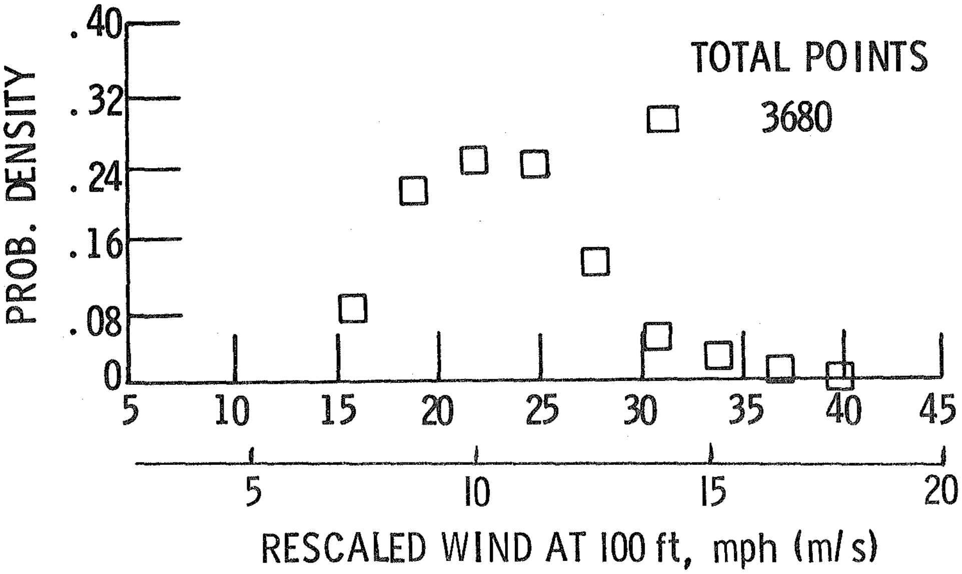


Note: The Line is the Least Squares Best-Fit Line to the Data. The Meteorogical Tower is Located 500 Feet from the Wind Turbine, and was Upwind of the Wind Turbine when the Data Reported here were Recorded.

Figure 9.1.1-2. Simultaneous Two-Minute Averages of Meterological Tower Wind Speed at 100 Feet vs. Nacelle Wind Speed.

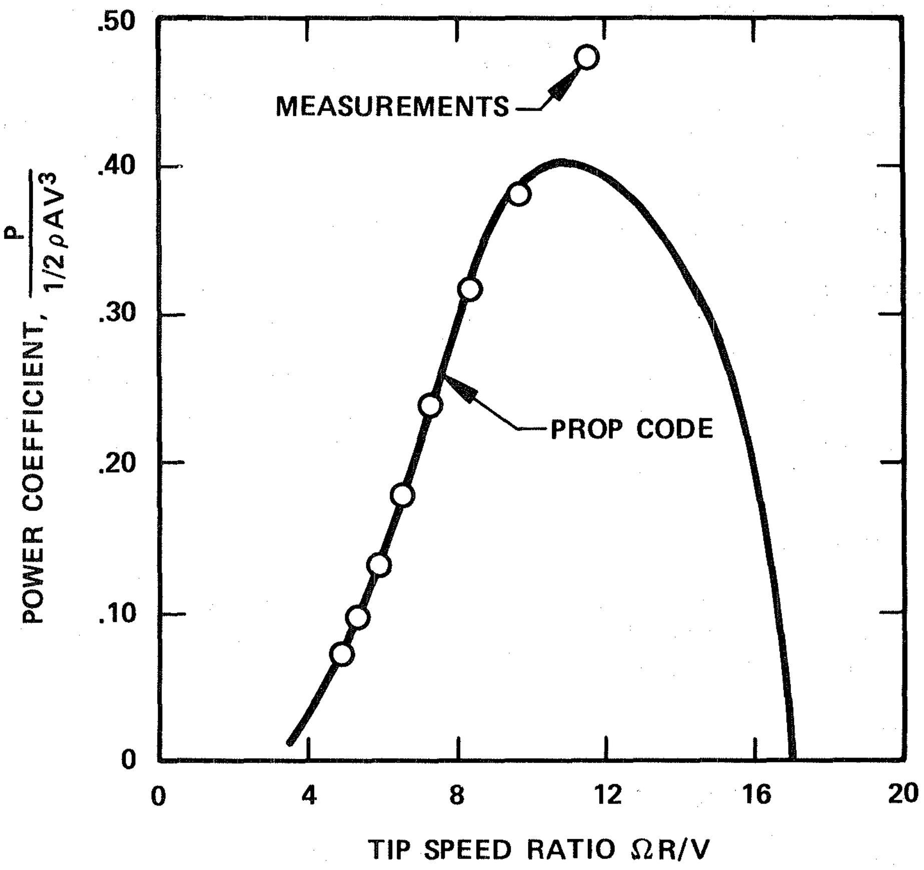


(a) ALTERNATOR POWER OUTPUT VS FREE-STREAM WIND SPEED AT HUB HEIGHT.



(b) HISTOGRAM OF WINDS FOR DATA SHOWN IN FIGURE (a).

Figure 9.1.1-3. Clayton, New Mexico: Power Versus Rescaled Wind at 100 Feet



P = power
ρ = air density
V = velocity of wind

A = rotor cross-sectional area
R = blade radius
Ω = rotor rotational speed

Figure 9.1.1-4, Power Coefficient vs. Tip Speed Ratio

comparison for the power vs. wind speed data shown in Figure 9.1.1-3. The power coefficient, C_p, is defined as the power delivered by the system divided by the total power available in the cross-sectional area of the windstream subtended by the wind turbine. Most of the preliminary data were taken above rated wind speed (tip speed ratio $< \sim 9$). The two data points taken below rated wind speed show reasonable agreement with predictions.

The data shown in Figures 9.1.1-3 (a) and (b) are explained as follows: the upper portion of the figure shows the statistics of groups of the measured parameters where the data are grouped into wind speed intervals of 3 mph (1.3 m/s) each. The symbols depicting the statistics of each group are defined as: the top bar on each symbol represents the upper bound of 84 percent of the data in the group, two symbols (squares) indicate the 90 percent confidence interval about the mean, and the lower dash represents the upper bound of the 16th percentile. This method of reducing data scatter for comparisons with theory and Sandia's "method of bins" share some common features, although this method retains more information. Both methods are applications of standard data analysis techniques. Figure 9.1.1-3 (b) shows the total number of data values analyzed, as well as the percentage of this total included in each group.

The comparison in Figure 9.1.1-3 (a) shows general agreement between the theory (shown as the solid line) and measured performance of the MOD-OA wind turbine. The deviation from theory (based on steady-state winds) near rated wind speed at the "sharp corner" of the curve, is well understood and has been discussed fully by Golding.[60] It is due to the fluctuation of the wind about its "steady" value which is equivalent to the wind turbine retaining an averaging on the two sides of the "corner".

9.1.2 DRIVE TRAIN EFFICIENCY

Figure 9.1.2-1 relates average rotor torque to average power for each revolution. These data result in the following correlation between alternator power output and rotor torque:

$$P_a = 0.00538\, T_r - 14.3$$

Where P_a = alternator power (kW)
T_r = rotor torque (ft-lbs)

The drive train efficiency, η_d, can be expressed as:

$$\eta_d = \frac{P_a}{P_r} = \frac{1.0}{1.077 + \frac{14.3}{P_a}}$$

where P_r = rotor power (kW)

Figure 9.1.2-2 shows a comparison of the constant design value for η_d of 0.75 and the measured values which range from 0.0 to 0.86.

The design value for the drive train efficiency represents a conservative average value which has been calculated by estimating the efficiencies of the various components from the rotor to the generator (at rated power). In

CLAYTON, NEW MEXICO

DRIVETRAIN PERFORMANCE

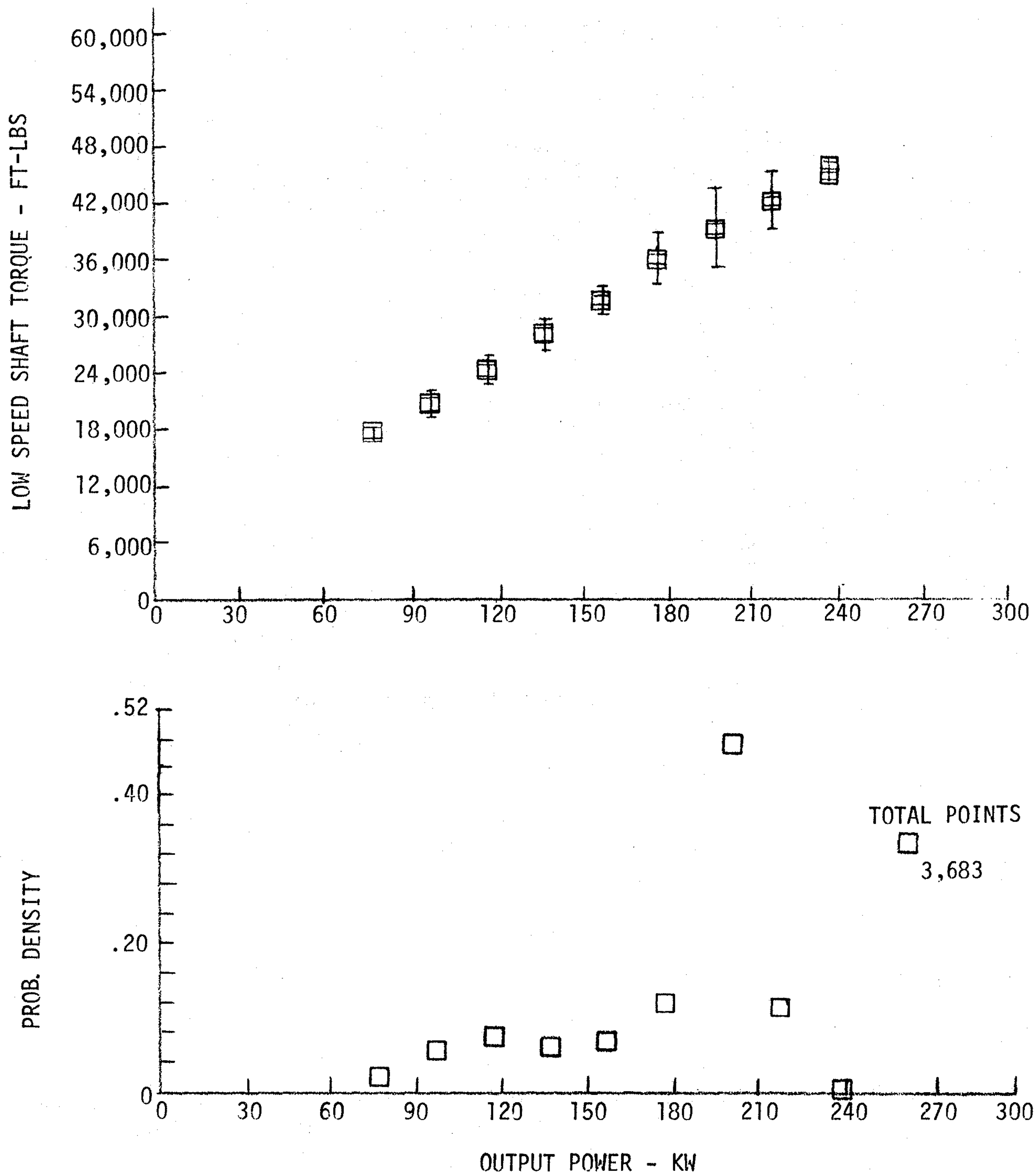


Figure 9.1.2-1. Average Rotor Torque vs. Average Power for Each Revolution

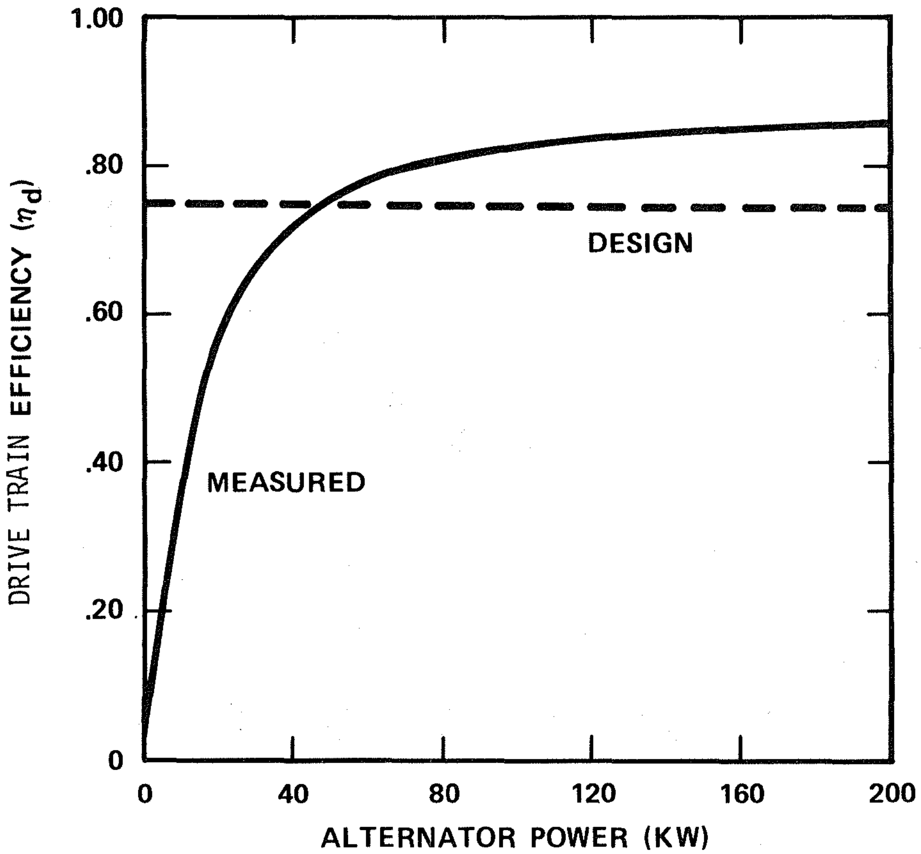


Figure 9.1.2-2. Comparison of the Design Value of Drive Train Efficiency with Measured Values at Various Alternator Powers

practice, these component efficiencies vary with rotor power. In particular, the generator efficiency increases sharply with increasing rotor power. Therefore, as alternator power approaches a significant fraction of rated output, the measured drive train efficiency coincides with the design value of 0.75 and in fact exceeds this value as the rated power of 200 kW(e) is achieved.

9.1.3 CYCLIC POWER

Cyclic power [(maximum-minimum)/two per revolution] is caused by both tower shadow and wind shear effects. The tower shadow effect is caused by the blades passing through the region of reduced wind speed downwind of the tower. The wind shear effect is caused by the blades passing through the variation in wind speed with height.

Figure 9.1.3-1 shows that the magnitude of the cyclic power on the average is less than $\pm$ 20 kW.

9.2 STRUCTURAL PERFORMANCE

The structural performance of the wind turbine during initial operation generally has been within predictions. This section presents comparisons of measured and calculated blade loads and examines the unsteady loads induced by tower shadow and wind shear effects.

9.2.1 MEAN AND CYCLIC LOADS

This section presents measured blade loads (at Station 40) from the wind turbine and compares these data with MOSTAB-WTE predictions. Both mean and cyclic loads are included.

All of the attached figures are presented in the same format: the upper portion of the figure shows the statistics of groups of the measured parameter -- where the data are grouped into wind speed "bins". The symbols depicting the statistics of each group are defined as follows: the top dash of the symbol represents the upper bound of 84 percent of the data in the group, two symbols indicate the 95 percent confidence interval about the mean, and the lower dash represents the upper bound of the 16th percentile. The MOSTAB-WTE predictions (shown in the figures as solid lines) are meant to represent the 84th percentile at all wind speeds, and thus should be compared with the upper dashes of the data. The lower portion of each figure shows the total number of data values analyzed, as well as the percentage of this total included in each group.

The cyclic loads experienced by the blades of the MOD-OA at Clayton, N.M. were somewhat lower than MOSTAB-WTE predictions, as shown in Figures 9.2.1-1 and 9.2.1-2.

The mean chordwise and flapwise loads matched the MOSTAB-WTE predictions very closely as seen in Figures 9.2.1-1 and 9.2.1-2.

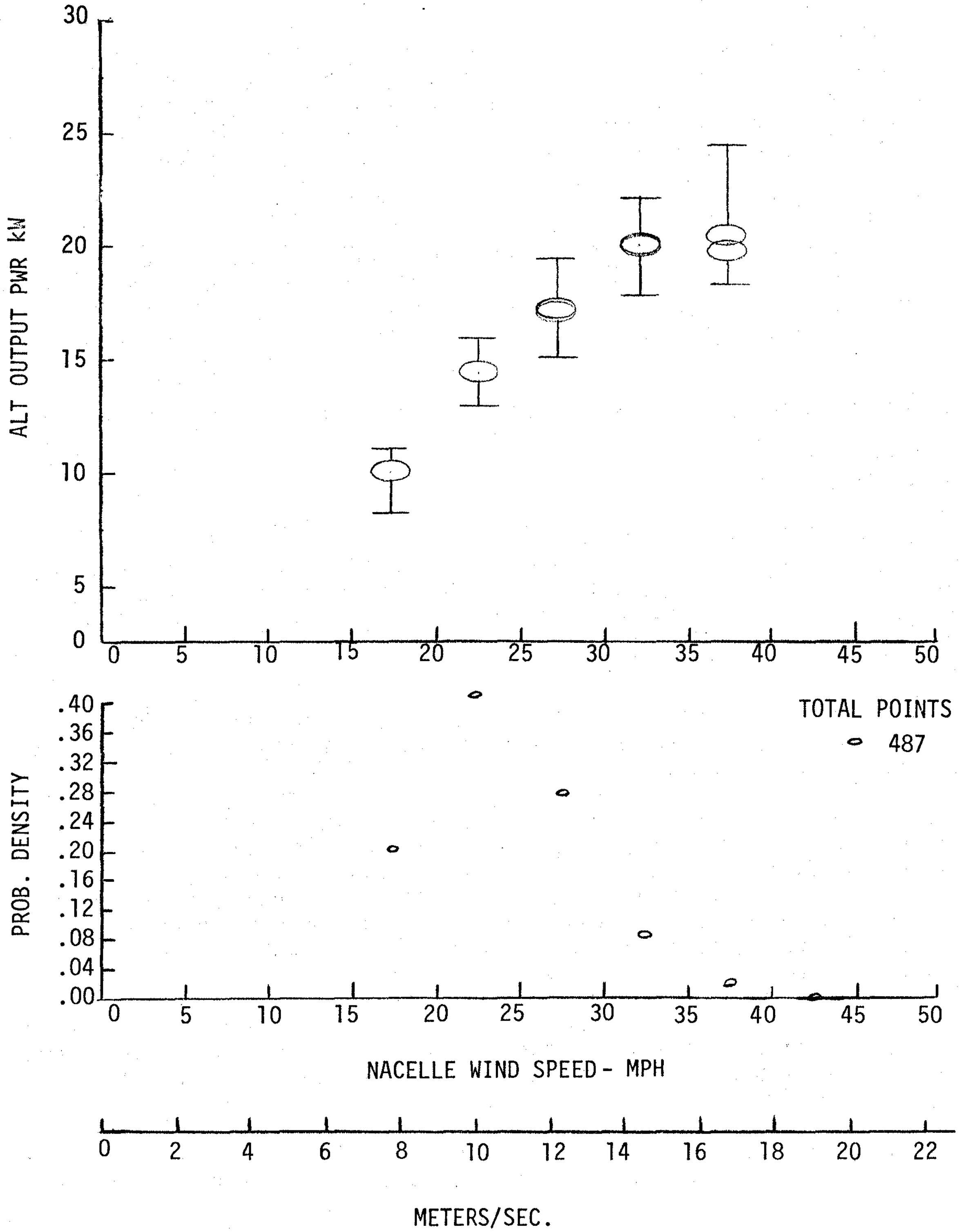


Figure 9.1.3-1. Cyclic Power vs. Wind Speed

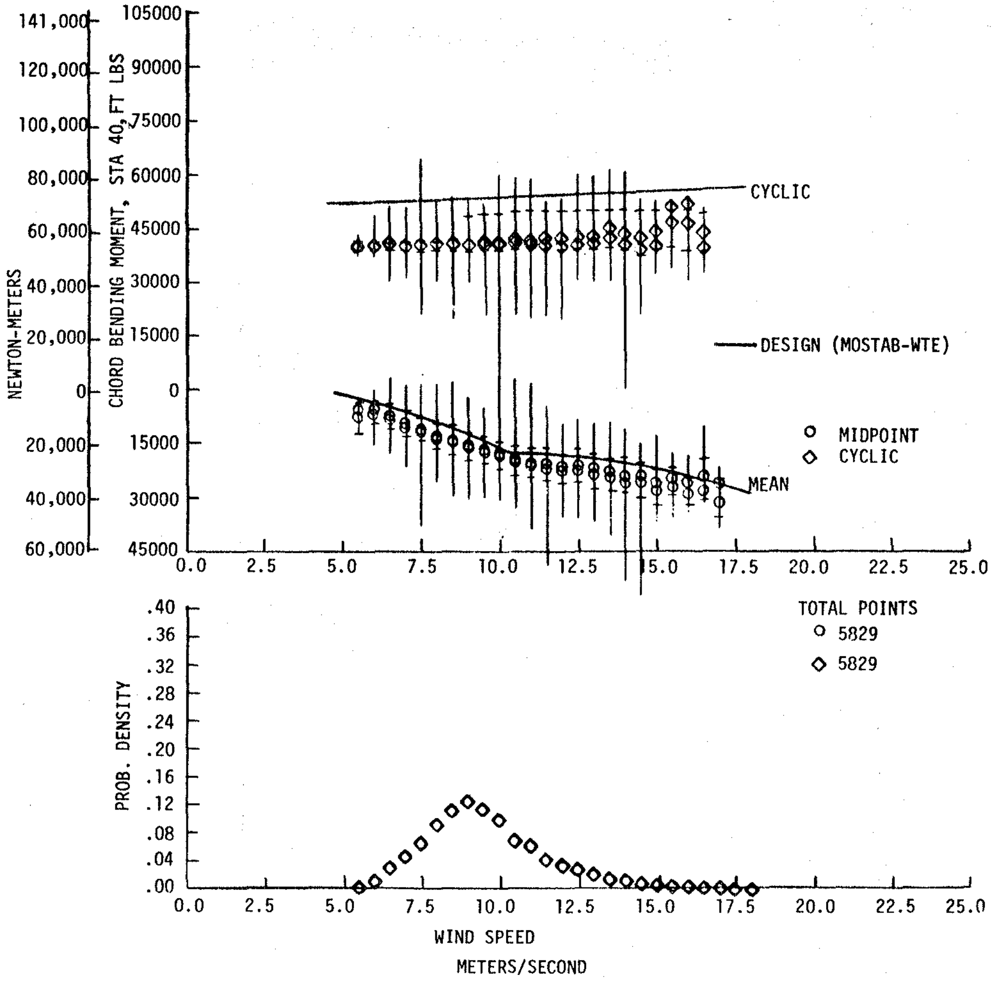


Figure 9.2.1-1. Mean and Cyclic Chordwise Loads at Station 40

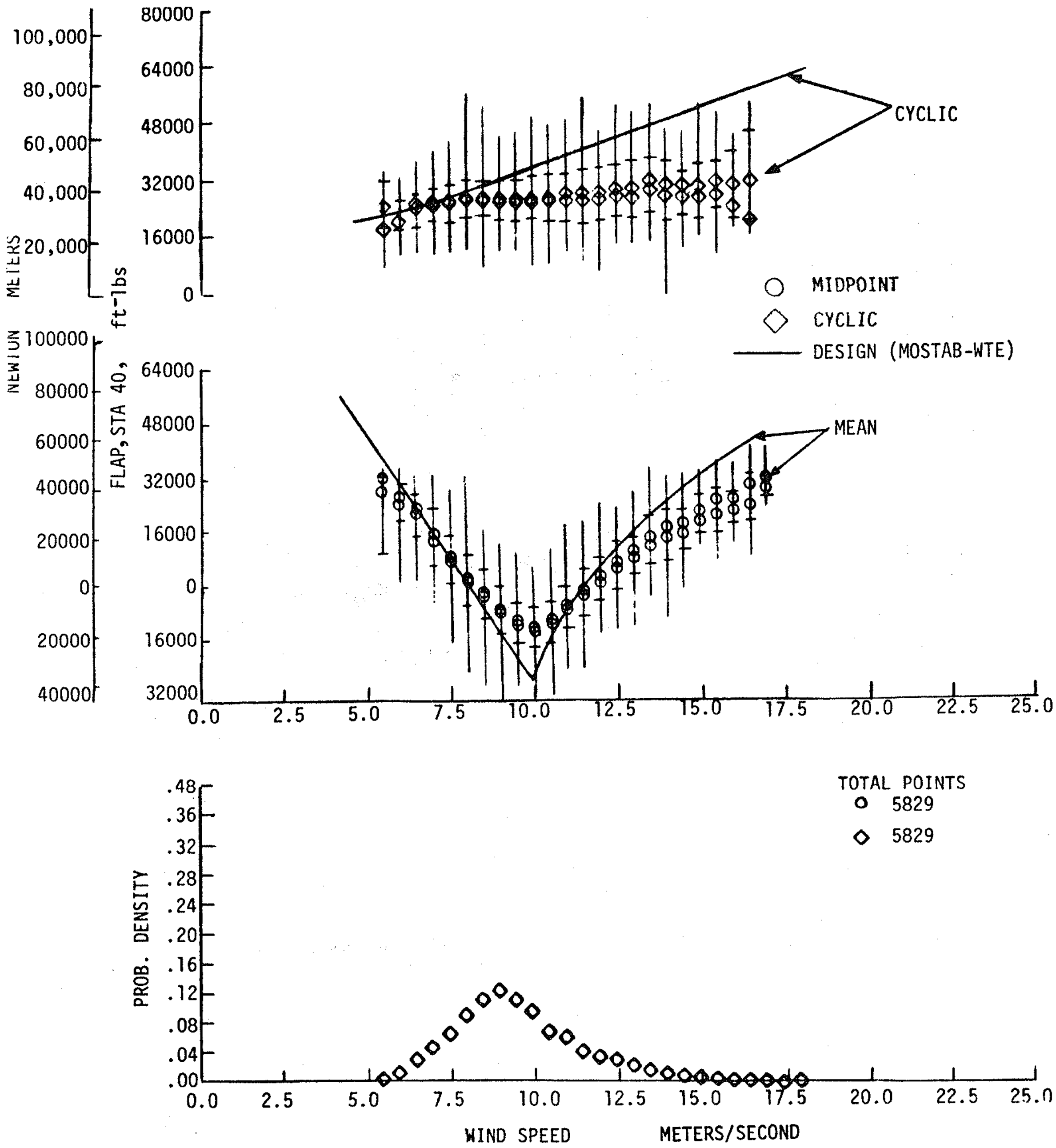


Figure 9.2.1-2. Mean and Cyclic Flapwise Loads at Station 40

The comparisons between the MOD-OA data and MOSTAB-WTE predictions presented here indicate good agreement between measured blade loads and estimated loads.

9.2.2 TOWER SHADOW AND WIND SHEAR EFFECTS

Figure 9.2.2-1 shows the strip chart records of flapwise and chordwise bending moments at station 40. Note the deviation from a pure sinusoidal waveform in the chordwise bending moment and the corresponding deviation in the flapwise bending moment. These are caused by both tower shadow and wind shear effects. Close examination reveals two deviations per revolution.

The large deviation is the direct effect on the blade from which the loads are measured. The smaller deviation is a result of the second blade experiencing the tower shadow and wind shear effects and communicating (via vibration, for example) this effect to the other blade.

Examination of the strip chart records reveals that tower shadow and wind shear are not negligible effects and should be considered in wind turbine structural analysis.

9.3 CONTROL SYSTEM PERFORMANCE

A description of the control systems is given in Section 2.10. This section will discuss the performance of the yaw control, pitch control and microprocessor control mechanisms of the wind turbine through the use of strip chart records which illustrate the behavior of these subsystems during operation.

9.3.1 YAW CONTROL

Figure 9.3.1-1 shows the results of typical yaw maneuvers. As the yaw brake pressure is reduced to allow realignment of the nacelle with the wind, the two yaw shaft loads change sharply. When yaw error is again within the 25° deadband, the brake pressure is increased to the maximum and the two yaw shaft loads are forced to steady values (i.e., the nacelle is clamped rigidly to the tower).

9.3.2 PITCH CONTROL

The pitch controller operates in one of three modes: position control used during the initial phase of rotor startup and during shutdown, speed control used in the intermediate phase of startup until electrical synchronization is achieved (i.e., from 5 rpm to 40 rpm) and closed loop power control used whenever the machine is synchronized to the utility grid. The blade pitch angle is driven toward zero degrees when the wind speed is below that required to produce 200 kW of power and the pitch angle is varied to spill wind when the wind speed is above this value to maintain a 200 kW power level. To shut the machine down, the blade pitch angle is reduced at a uniform rate until the blades are feathered at a pitch angle of -90°. The blades remain in feather position until a command to start is received.

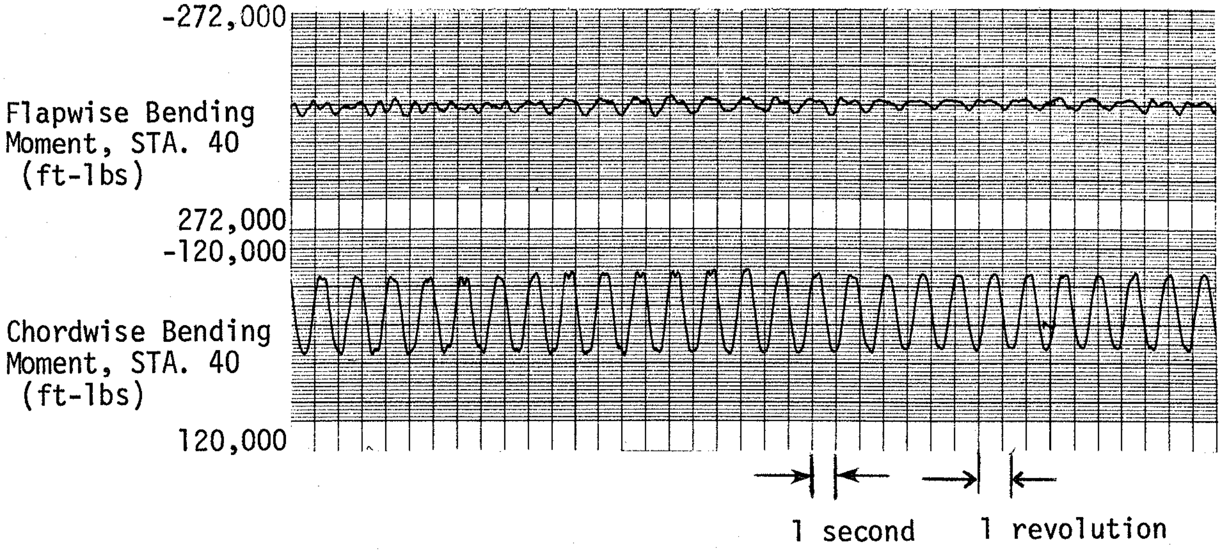


Figure 9.2.2-1. Strip Chart Records of Flapwise and Chordwise Bending Moments at Station 40

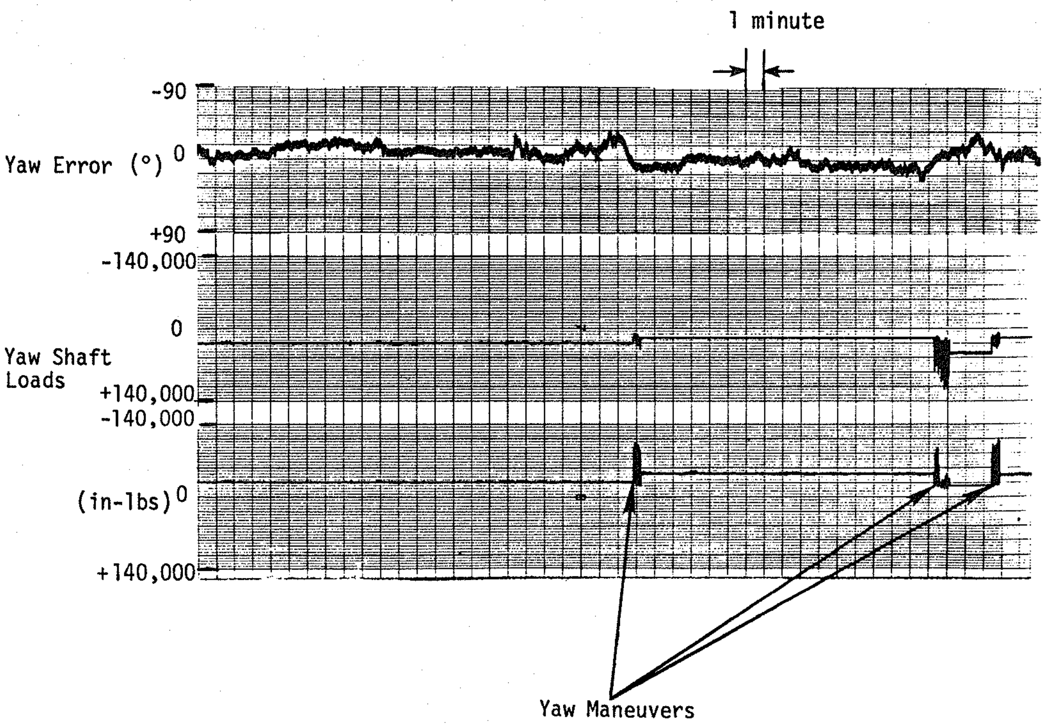


Figure 9.3.1-1. Strip Chart Records Illustrating Typical Yaw Maneuvers

Figure 9.3.2-1 shows strip chart records of alternator power, blade pitch angle, and rotor speed for startup conditions. Note that as blade pitch angle approaches 0°, the wind turbine rotor speed increases to 40 rpm. When 40 rpm is achieved, the machine is synchronized to the utility grid and alternator power is produced.

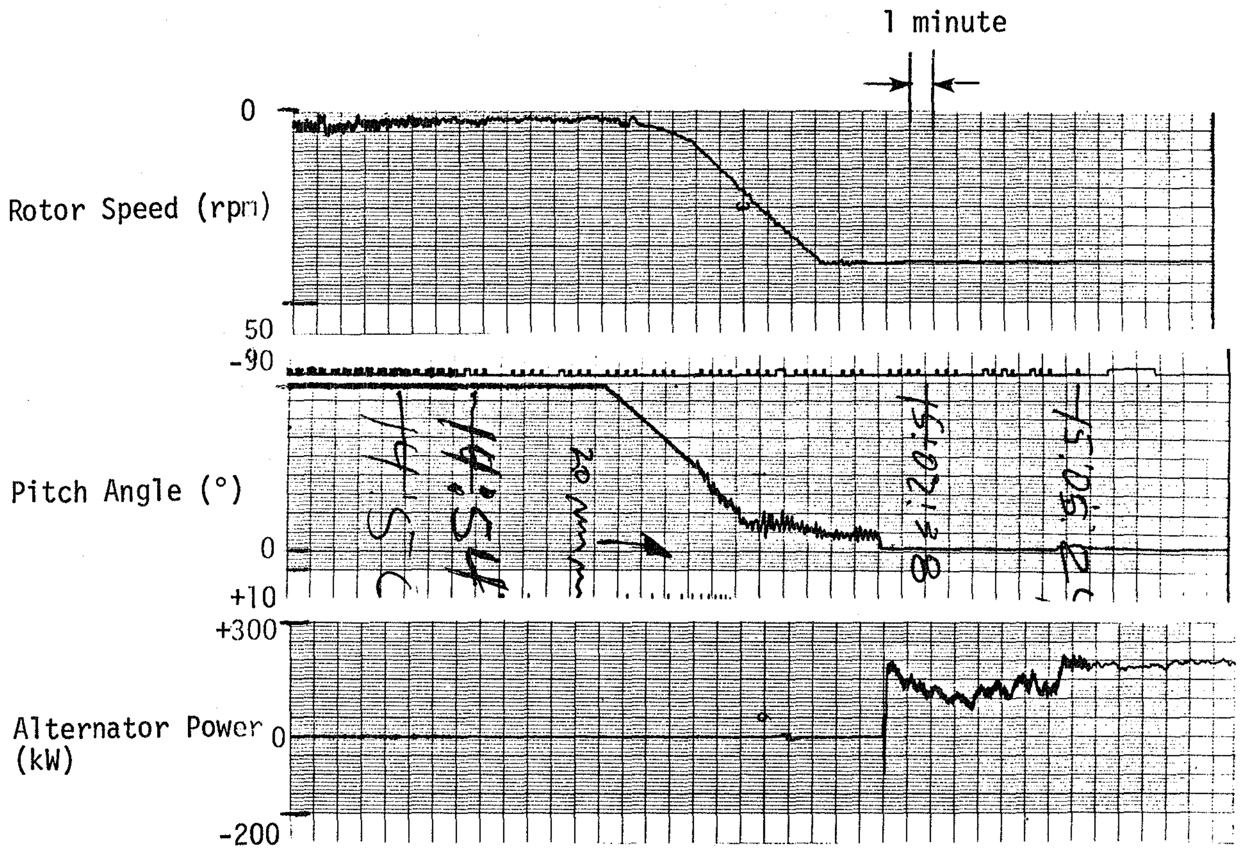


Figure 9.3.2-1. Rotor Speed, Blade Pitch Angle, and Alternator Power for Wind Turbine Startup

Figure 9.3.2-2 illustrates a shutdown of the wind turbine. Alternator power is reduced to zero, the blade pitch angle is changed at a constant rate to -90°, and the rotor speed is decreased from 40 rpm to 5 rpm.

9.3.3 MICROPROCESSOR CONTROL

The microprocessor is the control unit which permits unattended automatic operation of the wind turbine to take place. Once activated, the microprocessor monitors the wind and initiates a startup sequence when the wind speed, measured on the nacelle, exceeds 12 mph (5.4 m/s). Once synchronized, the machine continues to operate until a wind speed below 9.6 mph (4.3 m/s) or above 40 mph (17.9 m/s) is reached. When either of these conditions is encountered, the microprocessor initiates the shutdown sequence and waits until

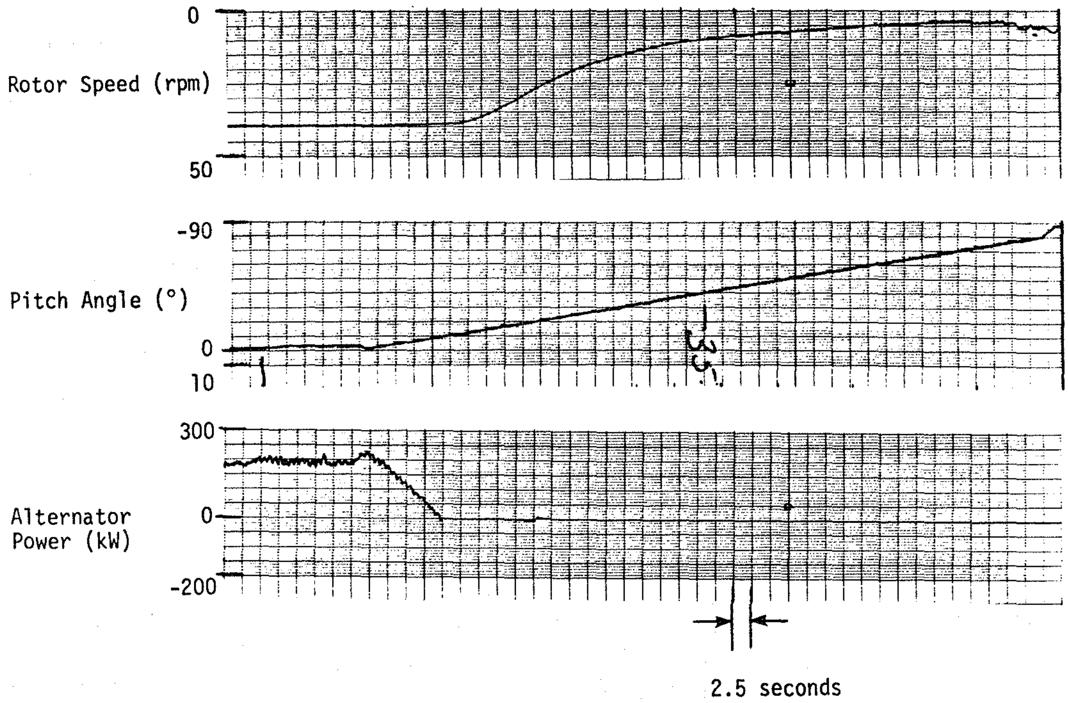


Figure 9.3.2-2. Rotor Speed, Blade Pitch Angle, and Alternator Power for Wind Turbine Shutdown

the wind speed either increases to the 12 mph (5.4 m/s) low wind value or drops to the 35 mph (15.6 m/s) high wind value required for a restart.

As an illustration of the start/stop control operation of the wind turbine, a low wind startup and shutdown is shown in Figure 9.3.3-1. Wind speed, power, and blade pitch angle are given. As wind speed reaches 12 mph (5.4 m/s), startup is initiated, blade pitch angle is increased to 0°, and alternator power is produced. However, after several minutes the wind speed dips below 9.6 mph (4.3 m/s) and a shutdown sequence is begun.

The microprocessor is also programmed to shut the wind turbine down whenever it detects certain abnormalties. These include slow startup or synchronization, loss of pitch hydraulic pressure, and loss of synchronization. Each of these abnormal conditions initiates the shutdown sequence and requires an on-site reset before normal operations can continue.

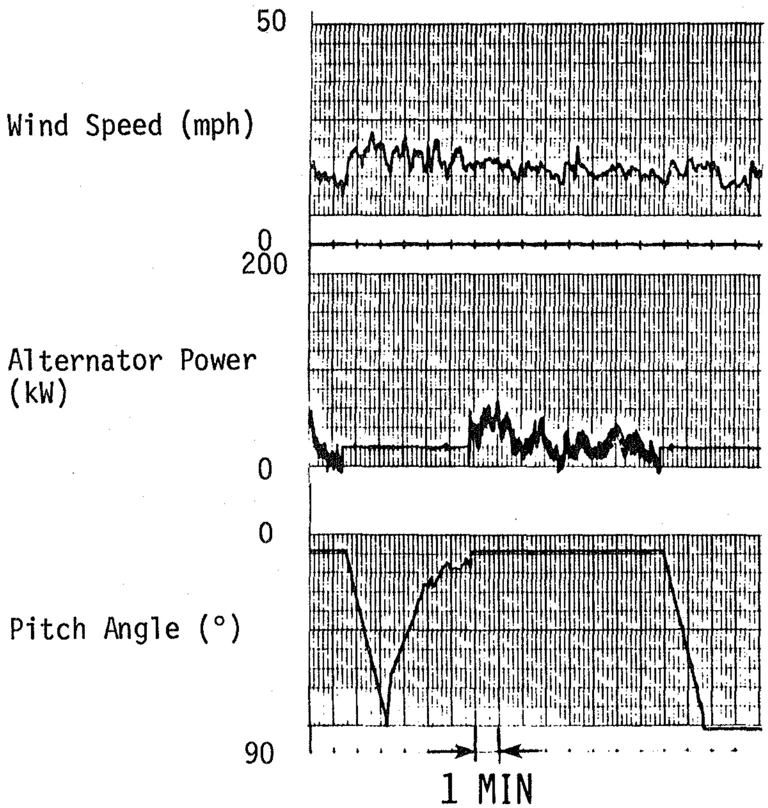


Figure 9.3.3-1. Low Wind Startup and Shutdown

9.4 UTILITY INTERFACE

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The wind generator has been placed near the end of one of the town's seven power feeders, about a half mile from the power plant. It produces power at 480 V, stepped up through a transformer to 2400 V, the level at which power is distributed. Clayton's municipal electric system has a radial configuration, with seven diesel generators in the central plant. Separate lines supply a hospital, high school, feed lot, and three residential feeders. A seventh line serves the internal needs of the power station. All generators feed into a common bus.

System operation consists of committing enough generating units to meet the total load and distributing the load among them on the basis of the operator's experience rather than a formal economic-dispatch strategy. One generator is designated the lead machine and made responsible for controlling the system frequency in response to load changes. All remaining machines are assigned a specific output (set-point loaded), but have droop (proportional) governor controls to regulate that output as their respective speeds change with

variations in system load. In essence the burden of maintaining system frequency falls almost entirely on the lead machine.

Each unit is a dual-fuel diesel capable of operating on diesel oil alone or on a mixture of 20 percent diesel oil and 80 percent natural gas. Each can be placed in service and fully loaded in a very short time - from three to seven minutes from a cold start, depending on its size. There are one 400 kW, one 1700 kW, two 1000 kW, and three 1250 kW units.

A combination of generators is chosen each day to satisfy the expected load. Typically the lead machine is one of the 1250 kW units, though it is rarely loaded to more than 1000 kW. It retains about 250 kW of spinning reserve for swing capability, since its output is constantly being adjusted to match the system's total generation to its total load. Enough generating units are then added at assigned outputs to provide the rest of the demand. The maximum set point load for any of these is typically 50 kW less than its rated output; as a generator approaches its limit, additional units are committed.

All of these dispatching decisions are left to the discretion of the system operator, whose experience in most of the utility's 40 years of operation has kept downtime to a minimum. When a generator is lost and sufficient spinning generation is not available, manual load shedding is activated from the power station. Since critical community loads are separated by the various distribution circuits, some selectivity can be exercised during these emergency load-shedding periods.

The basic system-control philosophy is similar to that of most other utilities: system frequency and time are regulated. System frequency is determined by the lead unit, which corrects frequency errors by a simple reset control that balances total generator load to match the instantaneous demand. The set point units do not contribute directly to frequency regulation except as their output is altered by the droop controls. The droop value for these generators is normally set at a gain of 0.4 per unit to provide a fairly sluggish response to load changes. This value is very different from the ones used in large steam or hydro plants (typically 0.05 per unit), but not uncommon for diesel generators operating on a common bus where excessive fluctuation (hunting) might exist.

9.4.1 VOLTAGE VARIATIONS

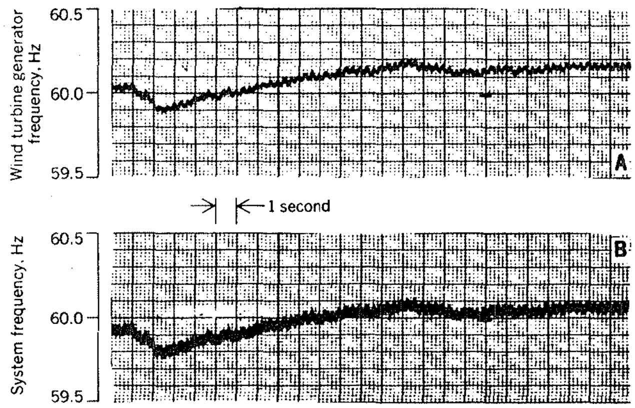
Output voltage regulation is described in Section 2.9. Initial operation of the wind turbine indicated normal functioning of the subsystem with no noticeable variations from the 480 volt nominal output.

9.4.2 FREQUENCY VARIATIONS

Since Clayton has a small, isolated diesel system with low inertia, the frequency-control specifications are somewhat different from those for large, interconnected utility systems. Instantaneous frequency is controlled within a peak-to-peak variation of approximately one Hz about the nominal value of 60 Hz, while the average system frequency is controlled by regulation of the time error. A quartz clock, calibrated against the national time standard, is used to maintain an error of less than 8 seconds. With the widely varying system

frequency, time corrections are often made through offsetting of the nominal system frequency reference on the lead unit.

The Clayton system frequency has a characteristic natural mode of oscillation (Fourier component) at three Hz. However, the presence of the wind machine does not affect this Fourier component (Figure 9.4.2-1). Although some recording noise does exist on the system frequency channel, the system frequency and the wind turbine frequency are identical. A wind turbine of the MOD-OA design exhibits several natural modes of oscillation - notably at 1.33 Hz, which is twice the blades' rotation speed. Oscillations at this frequency are created by both tower-shadow and wind-shear effects. The tower shadow effect is caused by the blades passing through the region of reduced wind speed downwind of the tower. The wind shear effect is caused by the blades passing through the variation in wind speed with height.



Note: System and Wind Turbine Frequency Characteristics are Identical in Clayton. The system frequency (B) also displays a noise component from the recording channel. A slight calibration error in the initial placement of the pen on the recording instrument causes display of a small, consistent offset between the system's frequency and the machine's. (From Reddoch and Klein[61])

Figure 9.4.2-1, System and Wind Turbine Frequency Characteristics - Clayton, N.M.

Such tower-shadow and wind-shear oscillations were found in early experiments with the test machine at the NASA Lewis Research Center. Because Clayton was to be the first utility demonstration of wind generators of that design, there was concern that the machine might excite natural oscillation modes in the Clayton system. Since the dominant mode of oscillation at Clayton is clearly three Hz, no such problems will occur.

There was also concern that undesirable interactions might occur between the diesel generators and the wind turbine's control systems. However, a study (as

cited in Reference 61) concluded that acceptable operation would result if wind-turbine power fluctuations caused by gusting stayed within the regulating capability of the diesels. Satisfactory operation has resulted.

The general performance of the Clayton system can best be characterized by four operating states:

1. Rated output of the wind generator during constant wind conditions and variations in system frequency (no significant load switchings, no new generator committment or generator-mix changes).

2. Significant system frequency excursions and smooth wind conditions.

3. Active wind conditions (gusting and turbulence) and little variation in system frequency.

4. Both active system and wind conditions.

During "ideal" conditions (Figure 9.4.2-2) where system and wind activity are both low, the wind machine's effect on the system is negligible. Peak-to-peak swings in the machine's power output reach a high of about 20 kW, which is smaller than the 50 kW swing observed in the output of diesel generators in the system.

Under variable system conditions, when the wind is fairly steady (Figure 9.4.2-2a) the average output power is a constant 200 kW (Figure 9.4.2-2c) and is unaffected by changes in system frequency. However, the peak-to-peak power swing of its output grows slightly, to about 30 kW.

When the conditions are reversed, a steady system with variable winds (Figure 9.4.2-3) the generator's output power tracks the wind velocity the instant it drops below the rated 22.4 mph (10.0 m/s). In that case, its power swings are slightly greater than those of the ideal case, but still less than the Clayton Station's typical power swings. System frequency variation is unaffected. Since the wind speed in Figure 9.4.2-3 is below rated velocity, the output power is determined by the characteristic response pattern shown in Section 2.12. During gusting at less than rated wind speeds, power output fluctuates in response to the wind since the machine's blades operate at a fixed pitch.

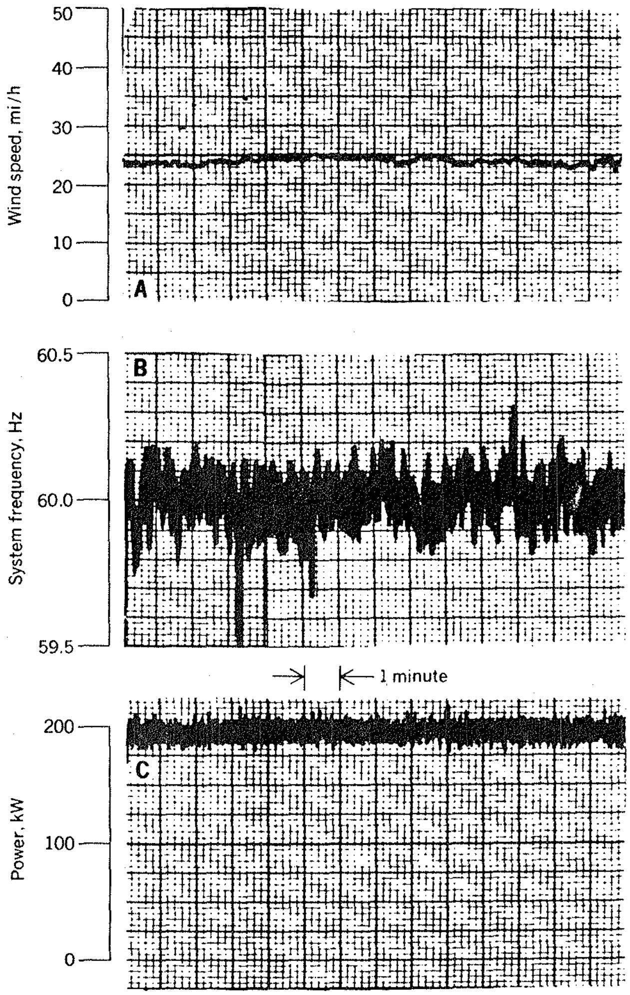
The worst case (Figure 9.4.2-4) occurs when both wind and system activity are high. Here again, the wind generator tracks the system frequency determined by the lead diesel, while wind-power output tracks the wind. Gusting clearly affects the amount of output power, but seems not to accentuate system frequency excursions. The lead machine does spend more effort regulating frequency, but its response capability is adequate to keep frequency variations within typical values. The pitch control maintains the average wind-power output at 200 kW, or at the appropriate power level predicted by the figure in Section 2.12.

Because of the high per-unit resistance of the distribution line connecting the wind generator to the central station, it appears that power oscillations caused by tower-shadow and wind-shear effects are attenuated to a level where they are too small to be sensed by the diesel generators.

9.5 ICE DETECTOR FOR BLADES

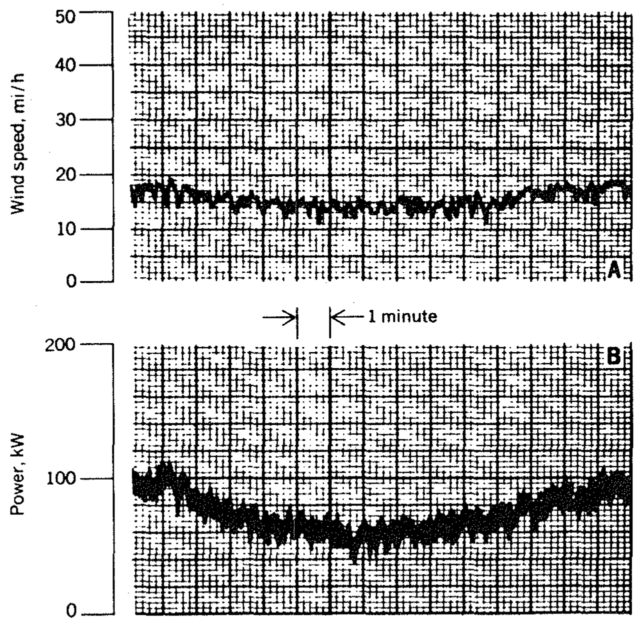
In March 1978, blade icing occurred on the wind turbine generator. At that time NASA LeRC personnel first observed large pieces of ice, scattered on the ground, adjacent to the wind turbine during operation. It was then observed that ice (see Figure 9.5-1) was shedding from the rotating blades. This situation posed a safety hazard for personnel and equipment that might have been in close proximity to the machine.

For personnel safety, NASA LeRC decided to provide an ice detector subsystem on the wind turbine. The control system was modified to monitor the ice detector signal and initiate shutdown of the wind turbine. The ice detector subsystem (Rosemount Inc. Model 871FA-122) was installed and operational at Clayton in November, 1978.



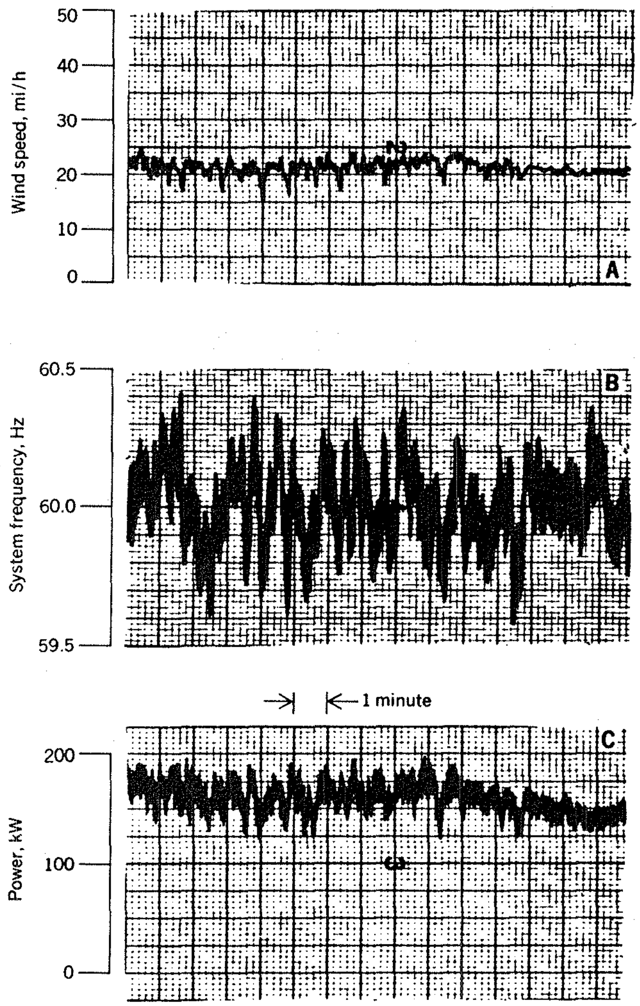
Note: With Constant Wind at or above Rated Velocities (A) and Small Frequency Excursions (B), the Clayton Wind Turbine Produces 200 kW of power (C). (From Reddoch and Klein[61])

Figure 9.4.2-2. Wind Speed, System Frequency and Power Versus Time with Constant Winds - Clayton, N.M.



Note: With Gusting (A) and Small Frequency Excursions, the Clayton Wind Turbine Produces Power (B) at a Level Determined by the Wind Speed, as shown by the Graph of Wind Speed vs. Output Power in Fig. 2.12-1. (From Reddoch and Klein[61])

Figure 9.4.2-3. Wind Speed and Power Versus Time With Gusting and Small Frequency Excursions - Clayton, N.M.



Note: Even with Wind Gusting (A) and Large System Frequency Excursions (B) - "Worst Case" Conditions - the Wind Generator Continues to Produce Power Close to its Rated Output (From Reddoch and Klein[61])

Figure 9.4.2-4. Wind Speed, System Frequency and Power versus Time with Gusting and Large Frequency Excursions - Clayton, N.M.

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Figure 9.5-1. Ice Shed From Blades

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APPENDIX A

LIST OF ENGINEERING DRAWINGS FOR THE MOD-OA WIND TURBINE INCLUDING THE WESTINGHOUSE AND NASA LEWIS RESEARCH CENTER DRAWING NUMBERS

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1015F01	11	CR758862	1	K	(NASA) MOD-OA 200 kW WIND TURBINE GENERATOR ASSEMBLY
		CR758863	1	G	(NASA) MOD-OA 200 kW WIND TURBINE GENERATOR ASSEMBLY
					(W) ASSEMBLY MOD-OA 200 kW WIND TURBINE GENERATOR
1015F02	1	CD758836	1	A	(NASA) HUB FORGING
					(W) HUB PITCH FORGING MOD-OA 200 kW WIND TURBINE GENERATOR
1015F03	4	CR758864	1	D	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB
		CD758875	1	C	(NASA) SUB-ASSEMBLY BEARING & GEAR ADJUSTMENT
					(W) PITCH CONTROL HUB ASS'Y MOD-OA 200 kW WIND TURB. GEN.
1015F04	1	CF758865	1	B	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 1
					(W) HUB PITCH DETAIL MOD-OA 200 kW WIND TURBINE GENERATOR
1015F05	1	CD758866	1	A	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 2
					(W) BLADE SPINDLE SLEEVE MOD-OA 200 kW WIND TURBINE GEN.
1015F06	1	CD758867	1	D	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 3
					(W) BLADE SPINDLE HOUSING MOD-OA 200 kW WIND TURBINE GEN.
1015F07	1	CD758868	1	C	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 4
					(W) DRIVE SHAFT BEARING RETAINER MOD-OA 200 kW WTG
1015F08	1	CD758869	1	B	(NASA) ASS'Y-GEAR TYPE PITCH CONTROL HUB-DETAILS 5 THRU 11
					(W) HUB PITCH DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F09	1	CD758870	1	B	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 12
					(W) HUB PITCH DRIVE SHAFT MOD-OA 200 kW WIND TURBINE GEN.
1015F10	1	CD758872	1	C	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 15
					(W) HUB PITCH BEVEL PINION GEAR MOD-OA 200 kW WTG
1015F11	1	CD758873	1	C	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 16
					(W) HUB PITCH BEVEL GEAR SECTOR MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision - (i.e., Unrevised)

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1015F12	1	CF758874	1	C	(NASA) ASS'Y-GEAR TYPE PITCH CONTROL HUB-DETAILS 17 THRU 25 (W) HUB PITCH DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F14	6	CR758877	1	E	(NASA) BEDPLATE (W) BEDPLATE MOD-OA 200 kW WIND TURBINE GENERATOR
1015F15	3	CR758878	1	D	(NASA) FWD CENTER SHROUD (W) FORWARD CENTER SHROUD MOD-OA 200 kW WIND TURBINE GEN.
1015F16	4	CR758879	1	E	(NASA) REAR CENTER SHROUD (W) REAR CENTER SHROUD MOD-OA 200 kW WIND TURB. GENERATOR
1015F17	1	CF758880	1	A	(NASA) NOSE CONE (W) NOSE CONE MOD-OA 200 kW WIND TURBINE GENERATOR
1015F18	1	CF758881	1	C	(NASA) PROP CONE (W) PROP CONE (SPINNER) MOD-OA 200 kW WIND TURBINE GEN.
1015F19	1	CD758882	1	B	(NASA) PROP HUB & CONE COVER PLATE (W) BLADE OPENING COVERS MOD-OA 200 kW WIND TURBINE GEN.
1015F20	1	CD758883	1	-	(NASA) CONE SUPPORT DETAILS (W) CONE SUPPORT DETAILS MOD-OA 200 kW WIND TURBINE GEN.
1015F21	1	CD758884	1	A	(NASA) FRONT HUB SUPPORT (W) MOUNTING PANEL-PROP CONE MOD-OA 200 kW WIND TURB. GEN.
1015F22	1	CD758885	1	-	(NASA) REAR HUB SUPPORT (W) SUPPORT-PROP CONE MOD-OA 200 kW WIND TURBINE GENERATOR
1015F23	2	CF758886	1	C	(NASA) WALKWAYS (W) WALKWAYS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F24	1	CF758887	1	A	(NASA) ADJ. GENERATOR BOTTOM PLATE (W) BOTTOM PLATE-GENERATOR ADJUSTMENT MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

Sheet 2

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1015F25	1	CF758888	1	A	(NASA) ADJ. GEN. TOP & LOCK BAR (W) GENERATOR ADJUSTMENT DETAILS
1015F26	1	CF758889	1	C	(NASA) DETAILS (W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F27	1	CF758890	1	C	(NASA) MAIN DRIVE SHAFT (W) MAIN DRIVE SHAFT MOD-OA 200 kW WIND TURBINE GENERATOR
1015F28	1	CD758892	1	-	(NASA) BRAKE SUPPORT (W) BRAKE SUPPORT MOD-OA 200 kW WIND TURBINE GENERATOR
1015F29	1	CD758895	1	-	(NASA) PULLEY DRIVE SHAFT (W) PULLEY DRIVE SHAFT MOD-OA 200 kW WIND TURB. GENERATOR
1015F30	2	CR758896	1	E	(NASA) MAIN YAW BRG SUPPORT (W) MAIN YAW BRG SUPPORT MOD-OA 200 kW WIND TURBINE GEN.
1015F31	1	CF758897	1	A	(NASA) YAW DRIVE BRG HOUSING (W) YAW DRIVE BRG HOUSING MOD-OA 200 kW WIND TURBINE GEN.
1015F32	1	CF758898	1	-	(NASA) YAW DRIVE SHAFT (W) YAW DRIVE SHAFT MOD-OA 200 kW WIND TURBINE GENERATOR
1015F33	1	CF758899	1	-	(NASA) YAW BRG RETAINER & SEAL (W) YAW-BRG RETAINERS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F34	1	CD758900	1	A	(NASA) INTER. YAW DRIVE SHAFT (W) INTERMEDIATE YAW DRIVE SHAFT MOD-OA 200 kW WTG
1015F35	1	CD758901	1	B	(NASA) YAW DRIVE MOUNTING (W) YAW DRIVE MOUNTING PLATE MOD-OA 200 kW WIND TUR. GEN.
1015F36	1	CD758902	1	C	(NASA) SHEAR KEY & THRUST BUTTON (W) SHEAR KEY & THRUST BUTTON MOD-OA 200 kW WIND TUR. GEN.
1015F37	1	CC758903	1	B	(NASA) MAIN SLIP RING SUPPORT HORIZ. (W) MAIN SLIP RING SUPPORT (HORIZ.) MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1015F38	2	CF758904	1	C	(NASA) BREAK PRESS. SYST. (W) PIPING SCHEMATIC & PANEL LAYOUT BREAK CHAMBER & PRESSURIZING SYSTEM MOD-OA 200 kW WIND TURBINE GENERATOR
1015F39	1	CC758905	1	-	(NASA) LIFTING BOOM
		CC758907	1	-	(NASA) "U" BOLT - BOTTLE HOLD DOWN
		CC758931	1	A	(W) LIFTING BOOM, U-BOLT & WIND SPEED & DIRECTIONAL MOUNT. BRACKET MOD-OA 200 kW WIND TURBINE GENERATOR
1015F40	1	CD758906	1	-	(NASA) HYD PACK SUPPORT BED (W) HYDRAULIC PACKAGE SUPPORT BED MOD-OA 200 kW WTG
1015F41	1	CD758909	1	B	(NASA) LIFTING BEAM & SLING ASSEMBLY (W) LIFTING BEAM & SLING ASSEMBLY MOD-OA 200 kW WTG
1015F42	1	CD758908	1	A	(NASA) HYD PACK FAN SHROUD (W) HYDRAULIC PACKAGE FAN SHROUD MOD-OA 200 kW WTG
1015F43	3	CR758975	1	A	(NASA) SENSOR LOCATION (PLAN VIEW)
		CR758976	1	C	(NASA) SENSOR LOCATION (ELEVATION VIEW) (W) ELECTRICAL SENSOR LOCATIONS MOD-OA 200 kW WTG
1015F44	1	CF758910	1	B	(NASA) DETAILS (W) HIGH SPEED BRADE DETAILS MOD-OA 200 kW WIND TURB. GEN.
1015F45	1	CF758912	1	A	(NASA) ROTARY COUPLING SUPPORT (W) DEUBLIN CPLG SUPPORT BRACKET MOD-OA 200 kW WTG
1015F46	1	CD758913	1	B	(NASA) LADDER (W) LADDER WELDED ASSEMBLY MOD-OA 200 kW WIND TURB. GEN.
1015F47	1	CF758914	1	-	(NASA) REAR PROP CONE SUPPORTS (W) REAR PROP CONE SUPPORT MOD-OA 200 kW WIND TURBINE GEN.
1015F48	1	CD758915	1	A	(NASA) HYD SUPPLY CLAMP & SUPPORTS (W) HYDRAULIC SUPPLY CLAMP & SUPPORT MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

Sheet 4

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1015F49	2	CF758916	1	C	(NASA) CO AXIAL FLOW LINE ASSEMBLY (W) CO AXIAL FLOW LINE - ASSEMBLY & DETAIL MOD-OA 200 kW WIND TURBINE GENERATOR
1015F50	1	CD758919	1	A	(NASA) SPINNER RAIN GUARD (W) SPINNER RAIN GUARD MOD-OA 200 kW WIND TURBINE GENERATOR
1015F51	1	CF758920	1	A	(NASA) SLIP RING ANTI-ROTATION SUPPORT & BRKT. (W) SLIP RING ANTI-ROTATION SUPPORT & BRKT. MOD-OA 200 kW WIND TURBINE GENERATOR
1015F52	3	CF758921	1	A	(NASA) HYDRAULIC PUMP PACKAGE ASSEMBLY
		CF758922	1	A	
		CF758923	1	-	(W) HYDRAULIC PUMP PACKAGE ASSY MOD-OA 200 kW WTG
1015F53	2	CF758924	1	-	(NASA) DETAILS (W) HYDRAULIC PUMP PACKAGE ASSY MOD-OA 200 kW WTG
1015F54	1	CR758925	1	-	(NASA) DETAILS (W) HYDRAULIC PUMP DETAILS MOD-OA 200 kW WIND TURB. GEN.
1015F55	4	CR758926	1	B	(NASA) ACTUATOR ASSEMBLY (W) ACTUATOR ASSEMBLY MOD-OA 200 kW WIND TURB. GEN.
1015F56	1	CF758927	1	A	(NASA) DETAILS (W) ACTUATOR ASSY DETAILS MOD-OA 200 kW WIND TURB. GEN.
1015F57	1	CF758928	1	A	(NASA) DETAILS (W) ACTUATOR ASSY DETAILS MOD-OA 200 kW WIND TURB. GEN.
1015F58	1	CF758929	1	B	(NASA) HYDRAULIC SCHEMATIC DIAGRAM
		CP758929	7	-	(NASA) OPERATIONAL REQUIREMENTS & PARTS LIST (W) CONTROL SCHEMATIC DIAGRAM MOD-OA 200 kW WTG
1015F59	1	CF758930	1	B	(NASA) INTERFACE-METAL BLADE TO PITCH CONTROL HUB (W) INTERFACE-BLADE TO HUB MOD-OA 200 kW WIND TURBINE GEN.

*All Westinghouse Drawings are Revision -

Sheet 5

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1015F60	1	None			(NASA) NONE (W) DETAILS MOD-OA 200 kW WTG
1015F61	1	CD758932	1	A	(NASA) UPPER BRAKE SUPPORT (W) UPPER BRAKE SUPPORT MOD-OA 200 kW WIND TURBINE GEN.
1015F62	1	CD758933	1	-	(NASA) TURNTABLE BEARING & GEAR ASSY (W) TURNTABLE BRG & GEAR ASSY MOD-OA 200 kW WIND TURB. GEN.
1015F63	1	CD758934	1	C	(NASA) LIFTING BEAM (W) LIFTING BEAM DETAILS MOD-OA 200 kW WIND TURBINE GEN.
1015F64	1	CF758936	1	A	(NASA) EXTERIOR FINISH-FIBERGLAS HOUSING (W) EXTERIOR FINISH-FIBERGLAS HOUSING MOD-OA 200 kW WTG
1015F65	1	CB758490 CC758937	1 1	A B	(NASA) BUTTRES RING RETAINER (NASA) TRANSFORMER BRACKETS (W) TRANSFORMER ANTI-ROTATION BRACKET & BUTTRES RING RETAINER DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F66	1	CD758938	1	-	(NASA) OUTPUT SHAFT CONFIGURATION FOR DOUBLE REDUCTION WORM GEAR UNIT (W) DOUBLE REDUCTION WORM GEAR UNIT YAW DRIVE MOD-OA 200 kW WIND TURBINE GENERATOR
1015F67	1	CF758939	1	A	(NASA) TOWER SLIP RING ANTI-ROTATION ASSEMBLY (W) TOWER SLIP RING ANTI-ROTATION ASSY MOD-OA 200 kW WTG
1015F68	1	CC758871 CC758945	1 1	A A	(NASA) DETAILS (NASA) BUTTRES RING (W) HUB PITCH DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F69	1	CF758946	1	B	(NASA) MOD OA WIND TURBINE GENERATOR SITE PLAN & GENERAL ASSY (W) SITE PLAN & GENERAL ASSY MOD-OA 200 kW WIND TURBINE GEN.

*All Westinghouse Drawings are Revision -

Sheet 6

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1015F70	4	CF758948	1	B	(NASA) STRUCTURAL-TOWER ELEVATION & DETAILS
		CF758949	1	A	(NASA) STRUCTURAL-TOWER PLANS & DETAILS
		CF758950	1	A	(NASA) STRUCTURAL-TOWER DETAILS
					(W) TOWER ELEVATIONS, PLAN & DETAILS MOD-OA 200 kW WTG
1015F71	2	CF758952	1	-	(NASA) STRUCTURAL-ASSEMBLY STAND PLAN & DETAILS (W) ASSY STAND PLAN & DETAILS MOD-OA 200 kW WIND TURB. GEN.
1015F72	1	CD758957	1	B	(NASA) SPEED INCREASER-DIMENSIONAL REQUIREMENTS (W) SPECIAL SPEED INCREASER MOD-OA 200 kW WIND TURBINE GEN.
1015F73	1	CC758972	1	A	(NASA) GEAR BOX SLIP RING ASSEMBLY (W) GEAR BOX SLIP RING ASSEMBLY-ELECTRICAL MOD-OA 200 kW WIND TURBINE GENERATOR
1015F74	1	CF758973	1	A	(NASA) TOWER SLIP RING ASSY-ELECTRICAL (W) TOWER SLIP RING ASSY (ELEC) MOD-OA 200 kW WTG
1015F75	1	CF758974	1	B	(NASA) TOWER SLIP RING ASSY-ELECTRICAL (W) TOWER SLIP RING ASSY (ELEC) MOD-OA 200 kW WTG
1015F76	2	CF758981	1	B	(NASA) ELECTRICAL-EQUIPMENT LAYOUT, LIGHTING, GROUNDING, & DETAILS (W) ELECTRICAL-EQUIPMENT LAYOUT, LIGHTING, GROUNDING & DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F77	2	CF758982	1	B	(NASA) ELECTRICAL-POWER CONTROL & INSTRUMENTATION TERMINAL BOXES & DETAILS (W) ELECTRICAL-POWER CONTROL & INSTRUMENTATION TERMINAL BOXES & DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F78	1	CD758999	1	-	(NASA) INTERMEDIATE SHAFT (W) HIGH SPEED SHAFT ASSEMBLY MOD-OA 200 kW WIND TURB. GEN.
1015F79	1	CF758973	1	A	(NASA) TOWER SLIP RING ASSY-ELECTRICAL
		CF758974	1	B	(NASA) TOWER SLIP RING ASSY-ELECTRICAL
					(W) TOWER SLIP RING ASSY MOD-OA 200 kW WIND TURBINE GEN.

*All Westinghouse Drawings are Revision -

Sheet 7

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1015F80	3	CF759019	1	G	(NASA) HYDRAULIC SCHEMATIC YAW BRAKE
		CF760485	1	A	(NASA) HYDRAULIC SYSTEM PANEL YAW BRAKE
					(W) YAW BRAKE HYDRAULIC SYSTEM PANEL & SCHEMATIC MOD-OA 200 kW WIND TURBINE GENERATOR
1015F81	1	CC759020	1	-	(NASA) SPACERS YAW COUPLINGS
		CC760504	1	B	(NASA) HUB SEAL HOLDER
					(W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F82	1	CF759021	1	-	(NASA) PULLY BEARING SUPPORT
					(W) PULLEY BEARING SUPPORT MOD-OA 200 kW WIND TURB. GEN.
1015F83	1	CD759023	1	A	(NASA) DETAILS FOR HYDRAULIC ACTUATOR
					(W) DETAILS FOR HYDRAULIC ACTUATOR MOD-OA 200 kW WTG
1015F84	1	CF759024	1	A	(NASA) DETAILS FOR PUMP PACKAGE
					(W) PUMP PACKAGE DETAILS MOD-OA 200 kW WIND TURBINE GEN.
1015F85	2	CF760271	1	A	(NASA) STRUCTURAL-ASSY STAND PLAN & DETAILS
					(W) ASSY STAND PLAN & DETAILS MOD-OA 200 kW WIND TURB. GEN.
1015F86	2	CF760300	1	-	(NASA) STRUCTURAL-TOWER & ASSY STAND-FOUNDATIONS & DETAILS-CLAYTON N.M.
					(W) TOWER & ASSY STAND FOUNDATION & DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F87	1	CC760476	1	-	(NASA) GREASE & PRESSURE FITTINGS
					(W) GREASE & PRESSURE FITTINGS MOD-OA 200 kW WTG
1015F88	1	CD760477	1	-	(NASA) HUB COUNTER WEIGHTS
					(W) HUB COUNTER WEIGHTS MOD-OA 200 kW WIND TURBINE GEN.
1015F89	1	CF760478	1	-	(NASA) DETAILS
					(W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F90	1	CF760484	1	A	(NASA) HYDRAULIC SYSTEM PANEL YAW BRAKE
					(W) HYDRAULICS COMPONENTS MTG PANEL MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

Sheet 8

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1015F91	1	CF760484	1	A	(NASA) HYDRAULIC SYSTEM PANEL YAW BRAKE (W) HYDRAULIC SYSTEM PANEL YAW BRAKE-STRUCTURAL SUPPORT MOD-OA 200 kW WIND TURBINE GENERATOR
1015F92	1	CD760486	1	A	(NASA) AIR BOTTLE GAGE BRACKET (W) AIR BOTTLE GAGE BRACKET DETAILS MOD-OA 200 kW WTG
1015F93	1	CC759000	1	A	(NASA) FLUID COUPLER ADAPTER
		CC760487	1	-	(NASA) GEAR ALT. LOW SPEED SHAFT (W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1015F94	1	CC760488	1	A	(NASA) DUBLIN MOUNT
		CC760500	1	-	(NASA) SLIP RING COVER (W) DUBLIN MOUNT & SLIP RING DUST COVER MOD-OA 200 kW WTG
1015F95	2	CF760506	1	-	(NASA) ELECTRICAL-LOW SPEED SHAFT STRAIN GAGE LOCATION CONNECTION DIAGRAM & INSTALLATION
		CF760520	1	-	(NASA) ELECTRICAL-LOW SPEED SHAFT STRAIN GAGE LOCATION (W) ELECTRICAL-LOW SPEED SHAFT STRAIN GAGE LOCATION MOD-OA 200 kW WIND TURBINE GENERATOR
1015F96	1	CF760491	1	-	(NASA) YAW BRAKE ASSEMBLY (W) YAW BRAKE ASSY MOD-OA 200 kW WIND TURBINE GENERATOR
1015F97	1	CD760492	1	-	(NASA) YAW BRAKE DETAILS (W) YAW BRAKE DETAIL MOD-OA 200 kW WIND TURBINE GENERATOR
1015F98	1	CD760493	1	-	(NASA) YAW BRAKE DETAILS (W) YAW BRAKE DETAIL MOD-OA 200 kW WIND TURBINE GENERATOR
1015F99	1	CC760512	1	-	(NASA) FIXTURE FOR SEAL INSTALLATION
		CD760513	1	-	(NASA) SEAL INSTALLATION INSTRUCTIONS (W) FIXTURES FOR SEAL INSTALLATION MOD-OA 200 kW WTG
1017F02	1	NONE			(NASA) NONE (W) GENERATOR TACH MOUNT ASSY WITH KEYS & DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR

*All Westinghouse Drawings are Revision -

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1017F03	2	NONE			(NASA) NONE (W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1017F04	1	NONE			(NASA) NONE (W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
1017F05	1	NONE			(NASA) NONE (W) HYDRAULIC FITTINGS MOD-OA 200 kW WIND TURBINE GENERATOR
1016F01	4	CF758968	1	C	(NASA) ELECTRICAL-INSTRUMENTATION SENSOR WIRING LIST
		CF758969	1	E	(NASA) ELECTRICAL-INSTRUMENTATION SENSOR WIRING LIST
		CF758970	1	C	(NASA) ELECTRICAL-INSTRUMENTATION SENSOR WIRING LIST (W) INSTRUMENTATION SENSOR WIRING LIST MOD-OA 200 kW WTG
1016F02	2	CF758971	1	E	(NASA) ELECTRICAL-POWER ONE LINE CONNECTION DIAGRAM & SCHEDULE OF DWG. (W) POWER ONE LINE CONNECTION DIAGRAM SCHEDULE OF DWG'S MOD-OA 200 kW WTG
1016F03	1	CF758977	1	C	(NASA) ELECTRICAL-AUXILIARY ELECTRONIC PACKAGE CONNECTION & INTERCONNECTION DIAGRAM (W) AUXILIARY ELECTRONIC PACKAGE CONNECTION & INTERCONNECTION DIAGRAM MOD-OA 200 kW WIND TURBINE
1016F04	2	CF758978	1	D	(NASA) ELECTRICAL-SENSOR IDENTIFICATION LIST (CLAYTON) (W) SENSOR IDENTIFICATION LIST MOD-OA 200 kW WIND TURBINE
1016F05	1	CF758979	1	F	(NASA) ELECTRICAL-CABLE INTERCONNECTION (W) ELECTRICAL-CABLE INTERCONNECTION MOD-OA 200 kW WTG
1016F06	1	CF758980	1	-	(NASA) ELECTRICAL-INSTRUMENTATION INTERCONNECTION DIAGRAM PHASE I TEST (W) INSTRUMENTATION INTERCONNECTION DIAGRAM LERC-ERB CW 22 PHASE I TEST MOD-OA 200 kW WIND TURBINE GENERATOR
1016F07	1	CF758983	1	C	(NASA) ELECTRICAL-GEAR BOX SLIP RING CONNECTION DIAGRAM (W) GEAR BOX SLIP RING CONNECTION DIAGRAM MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

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LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1016F08	1	CF758984	1	G	(NASA) ELECTRICAL-TOWER SLIP RING CONNECTION DIAGRAM (W) TOWER SLIP RING CONNECTION DIAGRAM MOD-OA 200 kW WTG
1016F09	1	CF758985	1	A	(NASA) ELECTRICAL-STATIC SHAFT TEST INTERCONNECTION DIAGRAM PHASE I TEST (W) STATIC SHAFT TEST INTERCONNECTION DIAGRAM LERC-ERB CW 22 PHASE I TEST MOD-OA 200 kW WIND TURBINE GENERATOR
1016F10	1	CF759025	1	C	(NASA) ELECTRICAL-TOWER SENSOR LOCATION PLAN, DETAILS, PIN LAYOUT & ELECTRICAL CONNECTION DIAGRAM (W) TOWER SENSOR LOCATION PLAN DETAILS, PIN LAYOUT & ELECTRICAL CONNECTION DIAG. MOD-OA 200 kW WIND TURBINE
1016F11	2	CF759026	1	E	(NASA) ELECTRICAL SAFETY SHUTDOWN-ELEMENTARY DIAGRAM (W) ELECTRICAL SAFETY SHUTDOWN-ELEMENTARY DIAGRAM MOD-OA 200 kW WIND TURBINE GENERATOR
1016F12	2	CF759027	1	F	(NASA) ELECTRICAL-CONTROL ELEMENTARY DIAGRAM (W) CONTROL ELEMENTARY DIAGRAM MOD-OA 200 kW WTG
1016F13	1	CF759028	1	D	(NASA) ELECTRICAL-YAW CONTROLLER CONNECTION DIAGRAM (W) YAW CONTROLLER CONNECTION DIAGRAM MOD-OA 200 kW WTG
1016F14	1	CF759029	1	A	(NASA) ELECTRICAL-MICROPROCESSOR FLOW DIAGRAM (W) MICROPROCESSOR FLOW DIAGRAM MOD-OA 200 kW WTG
1016F15	1	CF759030	1	C	(NASA) ELECTRICAL-CONNECTION DIAGRAM FOR PITCH CONTROLLER (W) ELECTRICAL CONNECTION DIAGRAM PITCH CONTROLLER MOD-OA 200 kW WIND TURBINE GENERATOR
1016F16	1	CF759031	1	E	(NASA) ELECTRICAL-MICROPROCESSOR BLOCK DIAGRAM (W) MICROPROCESSOR BLOCK DIAGRAM MOD-OA 200 kW WTG
1016F17	1	CF759032	1	E	(NASA) ELECTRICAL-SUPERVISORY CONTROLLER INTERCONNECTION CENTRAL & REMOTE (W) SUPERVISORY CONTROLLER INTERCONNECT CENTRAL & REMOTES STATIONS & DETAIL "A" MOD-OA 200 kW WIND TURBINE GENERATOR

*All Westinghouse Drawings are Revision -

LIST OF DRAWINGS FOR THE MOD-0A 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1016F18	2	CF759033	1	E	(NASA) ELECTRICAL-PITCH CONTROLLER SCHEMATIC (W) PITCH CONTROLLER SCHEMATIC MOD-0A 200 kW WIND TURBINE
1016F19	2	CF759034	1	F	(NASA) ELECTRICAL-CONTROL PANEL LAYOUTS & RELAY PANEL CONNECTION DIAGRAMS (W) CONTROL PANEL LAYOUTS & RELAY PANEL CONNECTION DIAGRAMS MOD-0A 200 kW WTG
1016F20	7	CF759035	1	C	(NASA) ELECTRICAL-480 V SWITCHGEAR ONE LINE DIAGRAM
		CF759036	1	E	(NASA) ELECTRICAL-480 V SWITCHGEAR-ELEMENTARY 3 LINE DIAGRAM
		CF759037	1	F	(NASA) ELECTRICAL-480 V SWITCHGEAR-UNIT NO. 1 CONNECTION DGM.
		CF759038	1	E	(NASA) ELECTRICAL-480 V SWITCHGEAR-UNIT NO. 2 CONNECTION DGM.
		CF759039	1	F	(NASA) ELECTRICAL-480 V SWITCHGEAR-UNIT NO. 3 CONNECTION DGM. (W) 480 V SWITCHGEAR WIRING DIAGRAM UNIT NOS. 1, 2 & 3 MOD-0A 200 kW WTG
1016F21	3	CF759040	1	D	(NASA) ELECTRICAL-CONNECTION DIAGRAM FOR TERMINAL BOXES 2B & 3B
		CF759041	1	E	(NASA) ELECTRICAL-CONNECTION DIAGRAM FOR TERMINAL BOXES 2A & 2B
		CF759042	1	D	(NASA) ELECTRICAL-CONNECTION DIAGRAM FOR TERMINAL BOXES NO. 4 (W) CONNECTION DIAGRAMS FOR TERMINAL BOXES, 2B, 3B, 2A, 3A & NO. 4 MOD-0A 200 kW WTG
1016F22	1	CF759043	1	F	(NASA) ELECTRICAL-ELECTRICAL CONNECTION DIAGRAM SAFETY SHUTDOWN PANEL (W) ELECTRICAL CONNECTION DIAGRAM SAFETY SHUTDOWN PANEL MOD-0A 200 kW WTG
1016F23	1	CF759044	1	E	(NASA) ELECTRICAL-YAW BRAKE ELEMENTARY & CONNECTION DIAGRAM (W) YAW BRAKE ELEMENTARY & CONNECTION DGM. MOD-0A 200 kW WTG
1016F24	1	CF759045	1	C	(NASA) ELECTRICAL-MICROPROCESSOR CIRCUIT CARD LOCATOR RACK A & RACK B (W) MICROPROCESSOR CIRCUIT CARD LOCATION, RACK A & RACK B MOD-0A 200 kW WTG

*All Westinghouse Drawings are Revision -

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LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1016F25	1	CF759047	1	D	(NASA) ELECTRICAL-YAW CONTROL PANEL LAYOUT (W) YAW CONTROL PANEL LAYOUT MOD-OA 200 kW WTG
1016F26	1	CF759048	1	D	(NASA) ELECTRICAL-CONTROL RACK ANALOG TERMINAL STRIP INTERCONNECTION (W) CONTROL RACK ANALOG TERMINAL STRIP INTERCONNECTION MOD-OA 200 kW WIND TURBINE GENERATOR
1016F27	1	CF759049	1	E	(NASA) ELECTRICAL-ELECTRICAL CONNECTION DIAGRAM AMPLIFIER PANEL (W) ELECTRICAL CONNECTION DIAGRAM AMPLIFIER PANEL MOD-OA kW WIND TURBINE GENERATOR
1016F28	4	CF760480	3	-	(NASA) ELECTRICAL-INTRUSION ALARM (W) INTRUSION ALARM SYSTEM ALARM SYSTEM & ELEC. ELEMENTARY CONNECTION DIAGRAM & INSTALLATION DETAIL MOD-OA 200 kW WTG
1016F30	1	CD760481 CD760482	1 1	B -	(NASA) ELECTRICAL-MICROPROCESSOR TIMER-CARD SCHEMATIC (NASA) ELECTRICAL-MICROPROCESSOR RELAY-CARD SCHEMATIC (W) MICROPROCESSOR TIMER-CARD AND RELAY-CARD SCHEMATIC MOD-OA 200 kW WTG
1016F31	1	CF760494	1	B	(NASA) ELECTRICAL-ELAPSE TME PANEL (W) ELAPSE TIME PANEL MOD-OA 200 kW WIND TURBINE GENERATOR
1016F32	1	CF760495	1	C	(NASA) ELECTRICAL-RECLOSER & CIRCUIT BREAKER NO. 2 ELEMENTARY & WIRING DIAGRAMS (W) RECLOSER & CIRCUIT BREAKER NO. 2 ELEMENTARY & WIRING DIAGRAMS MOD-OA 200 kW WIND TURBINE GENERATOR
1016F33	1	CF760496	1	D	(NASA) ELECTRICAL-CLIMATRONICS & REFERENCE PANEL CONNECTION DIAGRAM (W) ELECTRICAL CONNECTION DIAGRAM CLIMATRONICS & REFERENCE PANEL MOD-OA 200 kW WIND TURBINE GENERATOR
1016F34	1	CF760497	1	B	(NASA) ELECTRICAL-PITCH CONTROLLER INTERNAL TERMINATIONS (W) PITCH CONTROLLER INTERNAL TERMINATIONS MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF WESTINGHOUSE DRAWINGS TO NASA LEWIS RESEARCH CENTER DRAWINGS

WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV.	TITLE OF DRAWING
1016F35	1	CF760546	1	-	(NASA) ELECTRICAL-SYNCHRO-D.C. CONVERTER-AEROVANE TRANSLATER SCHEMATIC (W) SYNCRO-D.C. CONVERTER AEROVANE TRANSLATOR SCHEMATIC MOD-OA 200 kW WIND TURBINE GENERATOR
1016F36	1	CF760552	1	-	(NASA) DAYTRONICS CONNECTION DIAGRAM-ELECTRICAL (W) DAYTRONICS CONNECTION DIAGRAM MOD-OA 200 kW WTG
1016F37	1	CF760561	1	-	(NASA) ELECTRICAL-SCHEMATIC DIAGRAM-BLADE STRAIN SHUT DOWN CARD (W) BLADE STRAIN SHUT DOWN CARD SCHEMATIC DIAGRAM MOD-OA 200 kW WIND TURBINE GENERATOR
1016F38	1	CF760553	1	-	(NASA) ONE LINE (W) 480 V SWITCHGEAR ONE LINE DIAGRAM MOD-OA 200 kW WTG
1016F39	1	CF760554	1	-	(NASA) THREE LINE (W) 480 V SWITCHGEAR 3 LINE DIAGRAM MOD-OA 200 kW WTG
1016F40	1	CF760555	1	-	(NASA) SWITCHGEAR SCHEMATIC DIAG. (W) 480 V D.C. SWITCHGEAR SCHEMATIC DIAGRAM MOD-OA 200 kW WTG
1016F41	1	CB760556 CB760557	1 1	- -	(NASA) SWITCHGEAR SCHEMATIC DIAG. (NASA) SWITCHGEAR SCHEMATIC DIAG. (W) 48 V SWITCHGEAR SCHEMATIC DIAGRAM MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CD758836	1	A	1015F02	1	(NASA) HUB FORGING (W) HUB PITCH FORGING MOD OA-200 kW WIND TURBINE GENERATOR
CR758862	1	F	1015F01	11	(NASA) MOD-OA 200 kW WIND TURBINE GENERATOR ASSEMBLY (W) ASSEMBLY MOD-OA 200 kW WIND TURBINE GENERATOR
CR758863	1	G	1015F01	11	(NASA) MOD-OA 200 kW WIND TURBINE GENERATOR ASSEMBLY (W) ASSEMBLY MOD-OA 200 kW WIND TURBINE GENERATOR
CR758864	1	D	1015F03	4	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB (W) PITCH CONTROL HUB ASS'Y MOD-OA 200 kW WIND TURB. GEN.
CF758865	1	B	1015F04	1	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 1 (W) HUB PITCH DETAIL MOD-OA 200 kW WIND TURBINE GENERATOR
CD758866	1	A	1015F05	1	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 2 (W) BLADE SPINDLE SLEEVE MOD-OA 200 kW WIND TURBINE GEN.
CD758867	1	D	1015F06	1	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 3 (W) BLADE SPINDLE HOUSING MOD-OA 200 kW WIND TURBINE GEN.
CD758868	1	C	1015F07	1	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 4 (W) DRIVE SHAFT BEARING RETAINER MOD-OA 200 kW WTG
CD758869	1	B	1015F08	1	(NASA) ASS'Y-GEAR TYPE PITCH CONTROL HUB-DETAILS 5 THRU 11 (W) HUB PITCH DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CD758870	1	A	1015F09	1	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 12 (W) HUB PITCH DRIVE SHAFT MOD-OA 200 kW WIND TURBINE GEN.
CC758871	1	A	1015F68	1	(NASA) DETAILS (W) HUB PITCH DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR

*All Westinghouse Drawings are Revision -

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CD758872	1	C	1015F10	1	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 15 (W) HUB PITCH BEVEL PINION GEAR MOD-OA 200 kW WTG
CD758873	1	C	1015F11	1	(NASA) ASSEMBLY-GEAR TYPE PITCH CONTROL HUB - DETAIL 16 (W) HUB PITCH BEVEL GEAR SECTOR MOD-OA 200 kW WTG
CF758874	1	C	1015F12	1	(NASA) ASS'Y-GEAR TYPE PITCH CONTROL HUB-DETAILS 17 THRU 25 (W) HUB PITCH DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CD758875	1	C	1015F03	4	(NASA) SUB-ASSEMBLY BEARING & GEAR ADJUSTMENT (W) PITCH CONTROL HUB ASS'Y MOD-OA 200 kW WIND TURB. GEN.
CR758877	1	E	1015F14	6	(NASA) BEDPLATE (W) BEDPLATE MOD-OA 200 kW WIND TURBINE GENERATOR
CR758878	1	D	1015F15	3	(NASA) FWD CENTER SHROUD (W) FORWARD CENTER SHROUD MOD-OA 200 kW WIND TURBINE GEN.
CR758879	1	E	1015F16	4	(NASA) REAR CENTER SHROUD (W) REAR CENTER SHROUD MOD-OA 200 kW WIND TURB. GENERATOR
CF758880	1	A	1015F17	1	(NASA) NOSE CONE (W) NOSE CONE MOD-OA 200 kW WIND TURBINE GENERATOR
CF758881	1	C	1015F18	1	(NASA) PROP CONE (W) PROP CONE (SPINNER) MOD-OA 200 kW WIND TURBINE GEN.
CD758882	1	B	1015F19	1	(NASA) PROP HUB & CONE COVER PLATE (W) BLADE OPENING COVERS MOD-OA 200 kW WIND TURBINE GEN.
CD758883	1	-	1015F20	1	(NASA) CONE SUPPORT DETAILS (W) CONE SUPPORT DETAILS MOD-OA 200 kW WIND TURBINE GEN.
CD758884	1	A	1015F21	1	(NASA) FRONT HUB SUPPORT (W) MOUNTING PANEL-PROP CONE MOD-OA 200 kW WIND TURB. GEN.

*All Westinghouse Drawings are Revision -

Sheet 2

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CD758885	1	-	1015F22	1	(NASA) REAR HUB SUPPORT (W) SUPPORT-PROP CONE MOD-OA 200 kW WIND TURBINE GENERATOR
CF758886	1	C	1015F23	2	(NASA) WALKWAYS (W) WALKWAYS MOD-OA 200 kW WIND TURBINE GENERATOR
CF758887	1	A	1015F24	1	(NASA) ADJ. GENERATOR BOTTOM PLATE (W) BOTTOM PLATE-GENERATOR ADJUSTMENT MOD-OA 200 kW WTG
CF758888	1	A	1015F25	1	(NASA) ADJ. GEN. TOP & LOCK BAR (W) GENERATOR ADJUSTMENT DETAILS
CF758889	1	C	1015F26	1	(NASA) DETAILS (W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CF758890	1	C	1015F27	1	(NASA) MAIN DRIVE SHAFT (W) MAIN DRIVE SHAFT MOD-OA 200 kW WIND TURBINE GENERATOR
CD758892	1	-	1015F28	1	(NASA) BRAKE SUPPORT (W) BRAKE SUPPORT MOD-OA 200 kW WIND TURBINE GENERATOR
CD758895	1	-	1015F29	1	(NASA) PULLEY DRIVE SHAFT (W) PULLEY DRIVE SHAFT MOD-OA 200 kW WIND TURB. GENERATOR
CR758896	1	E	1015F30	2	(NASA) MAIN YAW BRG SUPPORT (W) MAIN YAW BRG SUPPORT MOD-OA 200 kW WIND TURBINE GEN.
CF758897	1	A	1015F31	1	(NASA) YAW DRIVE BRG HOUSING (W) YAW DRIVE BRG HOUSING MOD-OA 200 kW WIND TURBINE GEN.
CF758898	1	-	1015F32	1	(NASA) YAW DRIVE SHAFT (W) YAW DRIVE SHAFT MOD-OA 200 kW WIND TURBINE GENERATOR
CF758899	1	-	1015F33	1	(NASA) YAW BRG RETAINER & SEAL (W) YAW-BRG RETAINERS MOD-OA 200 kW WIND TURBINE GENERATOR
CD758900	1	A	1015F34	1	(NASA) INTER. YAW DRIVE SHAFT (W) INTERMEDIATE YAW DRIVE SHAFT MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

Sheet 3

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CD758901	1	B	1015F35	1	(NASA) YAW DRIVE MOUNTING (W) YAW DRIVE MOUNTING PLATE MOD-OA 200 kW WIND TUR. GEN.
CD758902	1	C	1015F36	1	(NASA) SHEAR KEY & THRUST BUTTON (W) SHEAR KEY & THRUST BUTTON MOD-OA 200 kW WIND TUR. GEN.
CC758903	1	B	1015F37	1	(NASA) MAIN SLIP RING SUPPORT HORIZ. (W) MAIN SLIP RING (HORIZ.) MOD-OA 200 kW WTG
CF758904	1	C	1015F38	2	(NASA) BREAK PRESS. SYST. (W) PIPING SCHEMATIC & PANEL LAYOUT BRAKE CHAMBER & PRESSURIZING SYSTEM MOD-OA 200 kW WIND TURBINE GEN.
CC758905	1	-	1015F39	1	(NASA) LIFTING BOOM (W) LIFTING BOOM, U-BOLT & WIND SPEED & DIRECTIONAL MOUNT BRACKET MOD-OA 200 kW WIND TURBINE GENERATOR
CD758906	1	-	1015F40	1	(NASA) HYD PACK SUPPORT BED (W) HYDRAULIC PACKAGE SUPPORT BED MOD-OA 200 kW WTG
CC758907	1	-	1015F39	1	(NASA) "U" BOLT - BOTTLE HOLD DOWN (W) LIFTING BOOM, U-BOLT & WIND SPEED & DIRECTIONAL MOUNT BRACKET MOD-OA 200 kW WIND TURBINE GENERATOR
CD758908	1	A	1015F42	1	(NASA) HYD PACK FAN SHROUD (W) HYDRAULIC PACKAGE FAN SHROUD MOD-OA 200 kW WTG
CD758909	1	B	1015F41	1	(NASA) LIFTING BEAM & SLING ASSEMBLY (W) LIFTING BEAM & SLING ASSEMBLY MOD-OA 200 kW WTG
CF758910	1	B	1015F44	1	(NASA) DETAILS (W) HIGH SPEED BRADE DETAILS MOD-OA 200 kW WIND TURB. GEN.

*All Westinghouse Drawings are Revision -

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LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CF758912	1	A	1015F45	1	(NASA) ROTARY COUPLING SUPPORT (W) DEUBLIN CPLG SUPPORT BRACKET MOD-OA 200 kW WTG
CD758913	1	B	1015F46	1	(NASA) LADDER (W) LADDER WELDED ASSEMBLY MOD-OA 200 kW WTG
CD758914	1	-	1015F47	1	(NASA) REAR PROP CONE SUPPORTS (W) REAR PROP CONE SUPPORT MOD-OA 200 kW WTG
CD758915	1	A	1015F48	1	(NASA) HYD SUPPLY CLAMP & SUPPORTS (W) HYDRAULIC SUPPLY CLAMP & SUPPORT MOD-OA 200 kW WTG
CD758916	1	C	1015F49	1	(NASA) CO AXIAL FLOW LINE ASSEMBLY (W) CO AXIAL FLOW LINE - ASSEMBLY & DETAIL MOD-OA 200 kW WTG
CD758919	1	A	1015F50	1	(NASA) SPINNER RAIN GUARD (W) SPINNER RAIN GUARD MOD-OA 200 kW WTG
CF758920	1	A	1015F51	1	(NASA) SLIP RING ANTI-ROTATION & BRKT. (W) SLIP RING ANTI-ROTATION SUPPORT & BRT. MOD-OA 200 kW WTG
CF758921	1	A	1015F52	3	(NASA) HYDRAULIC PUMP PACKAGE ASSEMBLY (W) HYDRAULIC PUMP PACKAGE ASSY MOD-OA 200 kW WTG
CF758922	1	A	1015F52	3	(NASA) HYDRAULIC PUMP PACKAGE ASSEMBLY (W) HYDRAULIC PUMP PACKAGE ASSY MOD-OA 200 kW WTG
CF758923	1	-	1015F52	3	(NASA) HYDRAULIC PUMP PACKAGE ASSEMBLY (W) HYDRAULIC PUMP PACKAGE ASSY MOD-OA 200 kW WTG
CF758924	1	-	1015F53	2	(NASA) DETAILS (W) HYDRAULIC PUMP PACKAGED ASSY MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CF758925	1	-	1015F54	1	(NASA) DETAILS (W) HYDRAULIC PUMP DETAILS MOD-OA 200 kW WIND TURB. GEN.
CR758926	1	B	1015F55	4	(NASA) ACTUATOR ASSEMBLY (W) ACTUATOR ASSEMBLY MOD-OA 200 kW WIND TURB. GEN.
CF758927	1	A	1015F56	1	(NASA) DETAILS (W) ACTUATOR ASSY DETAILS MOD-OA 200 kW WIND TURB. GEN.
CF758928	1	A	1015F57	1	(NASA) DETAILS (W) ACTUATOR ASSY DETAILS MOD-OA 200 kW WIND TURB. GEN.
CF758929	1	B	1015F58	1	(NASA) HYDRAULIC SCHEMATIC DIAGRAM (W) CONTROL SCHEMATIC DIAGRAM MOD-OA 200 kW WTG
CP758929	7	-	1015F58	1	(NASA) OPERATIONAL REQUIREMENTS & PARTS LIST (W) CONTROL SCHEMATIC DIAGRAM MOD-OA 200 kW WTG
CF758930	1	B	1015F59	1	(NASA) INTERFACE-METAL BLADE TO PITCH CONTROL HUB (W) INTERFACE-BLADE TO HUB MOD-OA 200 kW WIND TURBINE GEN.
CC758931	1	A	1015F39	1	(NASA) WWD SPEED MOUNTING BRK'D (W) LIFTING BOOM, U-BOLT & WIND SPEED & DIRECTIONAL MOUNT-BRACKET MOD-OA 200 kW WIND TURBINE GENERATOR
CD758932	1	A	1015F61	1	(NASA) UPPER BRAKE SUPPORT (W) UPPER BRAKE SUPPORT MOD-OA 200 kW WIND TURBINE GEN.
CD758933	1	-	1015F62	1	(NASA) TURNTABLE BEARING & GEAR ASSY. (W) TURNTABLE BRG. & GEAR ASSY MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

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LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CD758934	1	C	1015F63	1	(NASA) LIFTING BEAM (W) LIFTING BEAM DETAILS MOD-OA 200 kW WIND TURBINE GEN.
CF758936	1	A	1015F64	1	(NASA) EXTERIOR FINISH - FIBERGLASS HOUSING (W) EXTERIOR FINISH-FIBERGLAS HOUSING MOD-OA 200 kW WTG
CC758937	1	B	1015F65	1	(NASA) TRANSFORMER BRACKETS (W) TRANSFORMER ANTI-ROTATION BRACKET & BUTTRES RING RETAINER DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CD758938	1	-	1015F66	1	(NASA) OUTPUT SHAFT CONFIGURATION FOR DOUBLE REDUCTION WORM GEAR UNIT (W) DOUBLE REDUCTION WORM GEAR UNIT YAW DRIVE MOD-OA 200 kW WIND TURBINE GENERATOR
CF758939	1	A	1015F67	1	(NASA) TOWER SLIP RING ANTI-ROTATION ASSEMBLY (W) TOWER SLIP RING ANTI-ROTATION ASSY MOD-OA 200 kW WTG
CC758945	1	A	1015F68	1	(NASA) BUTTRES RING (W) HUB PITCH DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CF758946	1	B	1015F69	1	(NASA) MOD OA WIND TURBINE GENERATOR SITE PLAN & GENERAL ASSY (W) SITE PLAN & GENERAL ASSY MOD-OA 200 kW WIND TURBINE GEN.
CF758948	1	B	1015F70	4	(NASA) STRUCTURAL-TOWER ELEVATION & DETAILS (W) TOWER ELEVATIONS, PLAN & DETAILS MOD-OA 200 kW WTG
CF758949	1	A	1015F90	4	(NASA) STRUCTURAL-TOWER PLANS & DETAILS (W) TOWER ELEVATIONS, PLAN & DETAILS MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

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LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CF758950	1	A	1015F70	4	(NASA) STRUCTURAL-TOWER DETAILS (W) TOWER ELEVATIONS, PLAN & DETAILS MOD-OA 200 kW WTG
CF758952	1	-	1015F71	2	(NASA) STRUCTURAL-ASSEMBLY STAND PLAN & DETAILS (W) ASSY STAND PLAN & DETAILS MOD-OA 200 kW WIND TURB. GEN.
CD758957	1	B	1015F72	1	(NASA) SPEED INCREASER-DIMENSIONAL REQUIREMENTS (W) SPECIAL SPEED INCREASER MOD-OA 200 kW WIND TURBINE GEN.
CF758968	1	C	1016F01	4	(NASA) ELECTRICAL-INSTRUMENTATION SENSOR WIRING LIST (W) INSTRUMENTATION SENSOR WIRING LIST MOD-OA 200 kW WTG
CF758969	1	E	1016F01	4	(NASA) ELECTRICAL-INSTRUMENTATION SENSOR WIRING LIST (W) INSTRUMENTATION SENSOR WIRING LIST MOD-OA 200 kW WTG
CF758970	1	C	1016F01	4	(NASA) ELECTRICAL-INSTRUMENTATION SENSOR WIRING LIST (W) INSTRUMENTATION SENSOR WIRING LIST MOD-OA 200 kW WTG
CF758971	1	E	1016F02	2	(NASA) ELECTRICAL-POWER ONE LINE CONNECTION DIAGRAM & SCHEDULE OF DWG. (W) POWER ONE LINE CONNECTION DIAGRAM SCHEDULE OF DWG'S MOD-OA 200 kW WIND TURBINE GENERATOR
CC758972	1	A	1015F73	1	(NASA) GEAR BOX SLIP RING ASSEMBLY (W) GEAR BOX SLIP RING ASSY-ELECTRICAL MOD-OA 200 kW WTG
CF758973	1	A	1015F74 1015F79	1	(NASA) TOWER SLIP RING ASSY-ELECTRICAL (W) TOWER SLIP RING ASSY (ELEC) MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

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LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CF758974	1	B	1015F75 1015F79	1	(NASA) TOWER SLIP RING ASSY-ELECTRICAL (W) TOWER SLIP RING ASSY MOD-OA 200 kW WIND TURBINE GEN.
CR758975	1	A	1015F43	3	(NASA) SENSOR LOCATION (PLAN VIEW) (W) ELECTRICAL SENSOR LOCATIONS MOD-OA 200 kW WTG
CR758976	1	C	1015F43	3	(NASA) SENSOR LOCATION (ELEVATION VIEW) (W) ELECTRICAL SENSOR LOCATIONS MOD-OA 200 kW WTG
CF758977	1	C	1016F03	1	(NASA) ELECTRICAL-AUXILIARY ELECTRONIC PACKAGE CONNECTION & INTERCONNECTION DIAGRAM (W) AUXILIARY ELECTRONIC PACKAGE CONNECTION & INTERCONNECTION DIAGRAM MOD-OA 200 kW WIND TURBINE
CF758978	1	D	1016F04	2	(NASA) ELECTRICAL-SENSOR IDENTIFICATION LIST (CLAYTON) (W) SENSOR IDENTIFICATION LIST MOD-OA 200 kW WTG
CF758979	1	F	1016F05	1	(NASA) ELECTRICAL-CABLE INTERCONNECTION (W) ELECTRICAL-CABLE INTERCONNECTION MOD-OA 200 kW WTG
CF758980	1	-	1016F06	1	(NASA) ELECTRICAL-INSTRUMENTATION INTERCONNECTION DIAGRAM PHASE I TEST (W) INSTRUMENTATION INTERCONNECTION DIAGRAM LERC-ERB CW 22 PHASE I TEST MOD-OA 200 kW WIND TURBINE
CF758981	1	B	1015F76	2	(NASA) ELECTRICAL-EQUIPMENT LAYOUT, LIGHTING, GROUNDING &DETA (W) ELECTRICAL-EQUIPMENT LAYOUT, LIGHTING, GROUNDING DETAILS MOD-OA 200 kW WTG
CF758982	1	B	1015F77	2	(NASA) ELECTRICAL-POWER CONTROL & INSTRUMENTATION TERMINAL BOXES & DETAILS (W) ELECTRICAL-POWER CONTROL & INSTRUMENTATION TERMINAL BOXES MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CF758983	1	C	1016F07	1	(NASA) ELECTRICAL-GEAR BOX SLIP RING CONNECTION DIAGRAM (W) GEAR BOX SLIP RING CONNECTION DIAGRAM MOD-OA 200 kW WTG
CF758984	1	G	1016F08	1	(NASA) ELECTRICAL-TOWER SLIP RING CONNECTION DIAGRAM (W) TOWER SLIP RING CONNECTION DIAGRAM MOD-OA 200 kW WTG
CF758985	1	A	1016F09	1	(NASA) ELECTRICAL-STATIC SHAFT TEST INTERCONNECTION DIAGRAM PHASE I TEST (W) STATIC SHAFT TEST INTERCONNECTION DIAGRAM LERC-ERB CW 22 PHASE I TEST MOD-OA 200 kW WIND TURBINE GENERATOR
CD758999	1	-	1015F78	1	(NASA) INTERMEDIATE SHAFT (W) HIGH SPEED SHAFT ASSEMBLY MOD-OA 200 kW WIND TURB. GEN.
CC759000	1	A	1015F93	1	(NASA) FLUID COUPLER ADAPTER (W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CF759019	1	G	1015F80	3	(NASA) HYDRAULIC SCHEMATIC YAW BRAKE (W) YAW BRAKE HYDRAULIC SYSTEM PANEL & SCHEMATIC MOD-OA 200 kW WIND TURBINE GENERATOR
CC759020	1	-	1015F81	1	(NASA) SPACERS YAW COUPLINGS (W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CF759021	1	-	1015F82	1	(NASA) PULLY BEARING SUPPORT (W) PULLEY BEARING SUPPORT MOD-OA 200 kW WIND TURB. GEN.
CD759023	1	A	1015F83	1	(NASA) DETAILS FOR HYDRAULIC ACTUATOR (W) DETAILS FOR HYDRAULIC ACTUATOR MOD-OA 200 kW WTG
CF759024	1	A	1015F84	1	(NASA) DETAILS FOR PUMP PACKAGE (W) PUMP PACKAGE DETAILS MOD-OA 200 kW WIND TURBINE GEN.

*All Westinghouse Drawings are Revision -

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LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CF759025	1	C	1016F10	1	(NASA) ELECTRICAL-TOWER SENSOR LOCATION PLAN, DETAILS, PIN LAYOUT & ELECTRICAL CONNECTION DIAGRAM (W) TOWER SENSOR LOCATION PLAN DETAILS, PIN LAYOUT & ELECTRICAL CONNECTION DIAG. MOD-OA 200 kW WTG
CF759026	1	E	1016F11	2	(NASA) ELECTRICAL SAFETY SHUTDOWN-ELEMENTARY DIAGRAM (W) ELECTRICAL SAFETY SHUTDOWN-ELEMENTARY DIAGRAM MOD-OA 200 kW WIND TURBINE GENERATOR
CF759027	1	F	1016F12	2	(NASA) ELECTRICAL-CONTROL ELEMENTARY DIAGRAM (W) CONTROL ELEMENTARY DIAGRAM MOD-OA 200 kW WTG
CF759028	1	D	1016F13	1	(NASA) ELECTRICAL-YAW CONTROLLER CONNECTION DIAGRAM (W) YAW CONTROLLER CONNECTION DIAGRAM MOD-OA 200 kW WTG
CF759029	1	A	1016F14	1	(NASA) ELECTRICAL-MICROPROCESSOR FLOW DIAGRAM (W) MICROPROCESSOR FLOW DIAGRAM MOD-OA 200 kW WTG
CF759030	1	C	1016F15	1	(NASA) ELECTRICAL-CONNECTION DIAGRAM FOR PITCH CONTROLLER (W) ELECTRICAL CONNECTION DIAGRAM PITCH CONTROLLER MOD-OA 200 kW WIND TURBINE GENERATOR
CF759031	1	E	1016F16	1	(NASA) ELECTRICAL-MICROPROCESSOR BLOCK DIAGRAM (W) MICROPROCESSOR BLOCK DIAGRAM MOD-OA 200 kW WTG
CF759032	1	E	1016F17	1	(NASA) ELECTRICAL-SUPERVISORY CONTROLLER INTERCONNECTION CENTRAL & REMOTE (W) SUPERVISORY CONTROLLER INTERCONNECT CENTRAL & REMOTE STATIONS & DETAIL "A" MOD-OA 200 kW WIND TURBINE GENERATOR
CF759033	1	E	1016F18	2	(NASA) ELECTRICAL-PITCH CONTROLLER SCHEMATIC (W) PITCH CONTROLLER SCHEMATIC MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

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LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CF759034	1	F	1016F19	2	(NASA) ELECTRICAL-CONTROL PANEL LAYOUTS & RELAY PANEL CONNECTION DIAGRAMS (W) CONTROL PANEL LAYOUTS & RELAY PANEL CONNECTION DIAGRAMS MOD-OA 200 kW WIND TURBINE GENERATOR
CF759035	1	C	1016F20	7	(NASA) ELECTRICAL-480 V SWITCHGEAR ONE LINE DIAGRAM (W) 480 V SWITCHGEAR WIRING DIAGRAM UNIT NOS. 1, 2 & 3 MOD-OA 200 kW WIND TURBINE GENERATOR
CF759036	1	E	1016F20	7	(W) 480 V SWITCHGEAR WIRING DIAGRAM UNIT NOS. 1, 2 & 3 MOD-OA 200 kW WIND TURBINE GENERATOR
CF759037	1	F	1016F20	7	(W) 480 V SWITCHGEAR WIRING DIAGRAM UNIT NOS. 1, 2 & 3 MOD-OA 200 kW WIND TURBINE GENERATOR
CF759038	1	E	1016F20	7	(W) 480 V SWITCHGEAR WIRING DIAGRAM UNIT NOS. 1, 2 & 3 MOD-OA 200 kW WIND TURBINE GENERATOR

*All Westinghouse Drawings are Revision -

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LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CF759039	1	F	1016F20	7	(W) 480 V SWITCHGEAR WIRING DIAGRAM UNIT NOS. 1, 2 & 3 MOD-OA 200 kW WIND TURBINE GENERATOR
CF759040	1	D	1016F21	3	(NASA) ELECTRICAL-CONNECTION DGM.FOR TERMINAL BOXES 2B & 3B (W) CONNECTION DIAGRAMS FOR TERMINAL BOXES, 2B, 3B, 2A, 3A & NO. 4 MOD-OA 200 kW WIND TURBINE GENERATOR
CF759041	1	E	1016F21	3	(NASA) ELECTRICAL-CONNECTION DGM.FOR TERMINAL BOXES 2A & 2B (W) CONNECTION DIAGRAMS FOR TERMINAL BOXES, 2B, 3B, 2A, 3A & NO. 4 MOD-OA 200 kW WIND TURBINE GENERATOR
CF759042	1	D	1016F21	3	(NASA) ELECTRICAL-CONNECTION DIAGRAM FOR TERMINAL BOXES NO. 4 (W) CONNECTION DIAGRAMS FOR TERMINAL BOXES, 2B, 3B, 2A, 3A & NO. 4 MOD-OA 200 kW WIND TURBINE GENERATOR
CF759043	1	F	1016F22	1	(NASA) ELECTRICAL-ELECTRICAL CONNECTION DIAGRAM SAFETY SHUTDOWN PANEL (W) ELECTRICAL CONNECTION DIAGRAM SAFETY SHUTDOWN PANEL MOD-OA 200 kW WIND TURBINE GENERATOR
CF759044	1	E	1016F23	1	(NASA) ELECTRICAL-YAW BRAKE ELEMENTARY & CONNECTION DIAGRAM (W) YAW BRAKE ELEMENTARY & CONNECTION DGM. MOD-OA 200 kW WTG
CF759045	1	C	1016F24	1	(NASA) ELECTRICAL-MICROPROCESSOR CIRCUIT CARD LOCATOR RACK A & RACK B (W) MICROPROCESSOR CIRCUIT CARD LOCATION, RACK A & RACK B MOD-OA 200 kW WIND TURBINE GENERATOR

*All Westinghouse Drawings are Revision -

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CF759047	1	D	1016F25	1	(NASA) ELECTRICAL-YAW CONTROL PANEL LAYOUT (W) YAW CONTROL PANEL LAYOUT MOD-OA 200 kW WTG
CF759048	1	D	1016F26	1	(NASA) ELECTRICAL-CONTROL RACK ANALOG TERMINAL STRIP INTERCONNECTION (W) CONTROL RACK ANALOG TERMINAL STRIP INTERCONNECTION MOD-OA 200 kW WIND TURBINE GENERATOR
CF759049	1	E	1016F27	1	(NASA) ELECTRICAL-ELECTRICAL CONNECTION DIAGRAM AMPLIFIER PANEL (W) ELECTRICAL CONNECTION DIAGRAM AMPLIFIER PANEL MOD-OA 200 kW WIND TURBINE GENERATOR
CF760271	1	A	1015F85	2	(NASA) STRUCTURAL-ASSY STAND PLAN & DETAILS (W) ASSY STAND PLAN & DETAILS MOD-OA 200 kW WIND TURB. GEN.
CF760300	1	-	1015F86	2	(NASA) STRUCTURAL-TOWER & ASSY STAND-FOUNDATIONS & DETAILS-CLAYTON N.M. (W) TOWER & ASSY STAND FOUNDATION & DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CC760476	1	-	1015F87	1	(NASA) GREASE & PRESSURE FITTINGS (W) GREASE & PRESSURE FITTINGS MOD-OA 200 kW WTG
CD760477	1	-	1015F88	1	(NASA) HUB COUNTER WEIGHTS (W) HUB COUNTER WEIGHTS MOD-OA 200 kW WIND TURBINE GEN.
CF760478	1	-	1015F89	1	(NASA) DETAILS (W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CF760480	3	-	1016F28	4	(NASA) ELECTRICAL-INTRUSION ALARM (W) INTRUSION ALARM SYSTEM ALARM SYSTEM & ELEC. ELEMENTARY CONNECTION DIAGRAM & INSTALLATION DETAIL MOD-OA 200 kW WTG
CD760481	1	B	1016F30	1	(NASA) ELECTRICAL-MICROPROCESSOR TIMER-CARD SCHEMATIC (W) MICROPROCESSOR TIMER CARD-SCHEMATIC MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

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LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CD760482	1	B	1016F30	1	(NASA) ELECTRICAL-MICROPROCESSOR RELAY-CARD SCHEMATIC (W) MICROPROCESSOR RELAY CARD SCHEMATIC MOD-OA 200 kW WTG
CF760484	1	A	1015F90	1	(NASA) HYDRAULIC SYSTEM PANEL YAW BRAKE (W) HYDRAULICS COMPONENTS MTG PANEL MOD-OA 200 kW WTG
CF760484	1	A	1015F91	1	(NASA) HYDRAULIC SYSTEM PANEL YAW BRAKE (W) HYDRAULIC SYSTEM PANEL YAW BRAKE-STRUCTURAL SUPPORT MOD-OA 200 kW WIND TURBINE GENERATOR
CF760485	1	A	1015F80	3	(NASA) HYDRAULIC SYSTEM PANEL YAW BRAKE (W) YAW BRAKE HYDRAULIC SYSTEM PANEL & SCHEMATIC MOD-OA 200 kW WIND TURBINE GENERATOR
CD760486	1	A	1015F92	1	(NASA) AIR BOTTLE GAGE BRACKET (W) AIR BOTTLE GAGE BRACKET DETAILS MOD-OA 200 kW WTG
CC760487	1	A	1015F93	1	(NASA) GEAR ALT. LOW SPEED SHAFT (W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CC760488	1	A	1015F94	1	(NASA) DUBLIN MOUNT (W) DUBLIN MOUNT & SLIP RING DUST COVER MOD-OA 200 kW WTG
CB760490	1	A	1015F65	1	(NASA) BUTTRES RING RETAINER (W) TRANSFORMER ANTI-ROTATION BRACKET & BUTTRES RING RETAINER DETAILS MOD-OA 200 kW WTG
CF760491	1	-	1015F96	1	(NASA) YAW BRAKE ASSEMBLY (W) YAW BRAKE ASSY MOD-OA 200 kW WIND TURBINE GENERATOR
CD760492	1	-	1015F97	1	(NASA) YAW BRAKE DETAILS (W) YAW BRAKE DETAIL MOD-OA 200 kW WIND TURBINE GENERATOR
CD760493	1	-	1015F98	1	(NASA) YAW BRAKE DETAILS (W) YAW BRAKE DETAIL MOD-OA 200 kW WIND TURBINE GENERATOR

*All Westinghouse Drawings are Revision -

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CF760494	1	B	1016F31	1	(NASA) ELECTRICAL-ELAPSE TME PANEL (W) ELAPSE TIME PANEL MOD-OA 200 kW WIND TURBINE GENERATOR
CF760495	1	C	1016F32	1	(NASA) ELECTRICAL-RECLOSER & CIRCUIT BREAKER NO. 2 ELEMENTARY & WIRING DIAGRAMS (W) RECLOSER & CIRCUIT BREAKER NO. 2 ELEMENTARY & WIRING DIAGRAMS MOD-OA 200 kW WIND TURBINE GENERATOR
CF760496	1	D	1016F33	1	(NASA) ELECTRICAL-CLIMATRONICS & REFERENCE PANEL CONNECTION DIAGRAM (W) ELECTRICAL CONNECTION DIAGRAM CLIMATRONICS & REFERENCE PANEL MOD-OA 200 kW WIND TURBINE GENERATOR
CF760497	1	B	1016F34	1	(NASA) ELECTRICAL-PITCH CONTROLLER INTERNAL TERMINATIONS (W) PITCH CONTROLLER INTERNAL TERMINATIONS MOD-OA 200 WTG
CC760500	1	-	1015F94	1	(NASA) SLIP RING COVER (W) DUBLIN MOUNT & SLIP RING DUST COVER MOD-OA 200 kW WTG
CC760504	1	B	1015F81	1	(NASA) HUB SEAL HOLDER (W) DETAILS MOD-OA 200 kW WIND TURBINE GENERATOR
CF760506	1	-	1015F95	2	(NASA) ELECTRICAL-LOW SPEED SHAFT STRAIN GAGE LOCATION CONNECTION DIAGRAM & INSTALLATION (W) ELECTRICAL-LOW SPEED SHAFT STRAIN GAGE LOCATION MOD-OA 200 kW WIND TURBINE GENERATOR
CC760512	1	-	1015F99	1	(NASA) FIXTURE FOR SEAL INSTALLATION (W) FIXTURES FOR SEAL INSTALLATION MOD-OA 200 kW WTG

All Westinghouse Drawings are Revision -

Sheet 16

LIST OF DRAWINGS FOR THE MOD-OA 200 kW WIND TURBINE GENERATOR

CORRELATION OF NASA LEWIS RESEARCH CENTER DRAWINGS TO WESTINGHOUSE DRAWINGS

NASA LEWIS DRAWING NUMBER	NUMBER OF SHTS.	*REV	WESTINGHOUSE DRAWING NUMBER	NUMBER OF SHTS.	TITLE OF DRAWING
CD760513	1	-	1015F99	1	(NASA) SEAL INSTALLATION INSTRUCTIONS (W) FIXTURES FOR SEAL INSTALLATION MOD-OA 200 kW WTG
CF760520	1	-	1015F95	2	(NASA) ELECTRICAL-LOW SPEED SHAFT STRAIN GAGE LOCATION (W) ELECTRICAL-LOW SPEED SHAFT STRAIN GAGE LOCATION MOD-OA 200 kW WIND TURBINE GENERATOR
CF760546	1	-	1016F35	1	(NASA) ELECTRICAL-SYNCHRO-D.C. CONVERTER-AEROVANE TRANSLATER SCHEMATIC (W) SYNCRO-D.C. CONVERTER AEROVANE TRANSLATOR SCHEMATIC MOD-OA 200 kW WIND TURBINE GENERATOR
CF760552	1	-	1016F36	1	(NASA) DAYTRONICS CONNECTION DIAGRAM-ELECTRICAL (W) DAYTRONICS CONNECTION DIAGRAM MOD-OA 200 kW WTG
CF760553	1	-	1016F38	1	(NASA) ONE LINE (W) 480 V SWITCHGEAR ONE LINE DIAGRAM MOD-OA 200 kW WTG
CF760554	1	-	1016F39	1	(NASA) THREE LINE (W) 480 V SWITCHGEAR 3 LINE DIAGRAM MOD-OA 200 kW WTG
CF760555	1	-	1016F40	1	(NASA) SWITCHGEAR SCHEMATIC DIAG. (W) 480 V D.C. SWITCHGEAR SCHEMATIC DIAGRAM MOD-OA 200 kW WTG
CF760556	1	-	1016F41	1	(NASA) SWITCHGEAR SCHEMATIC DIAG. (W) 48 V SWITCHGEAR SCHEMATIC DIAGRAM MOD-OA 200 kW WTG
CF760557	1	-	1016F41	1	(NASA) SWITCHGEAR SCHEMATIC DIAG. (W) 48 V SWITCHGEAR SCHEMATIC DIAGRAM MOD-OA 200 kW WTG

*All Westinghouse Drawings are Revision -

NOTE: COPY OF SAFETY PERMIT REQUEST MUST BE POSTED WITH THIS PERMIT.

Rev. #8
July 15, 1978

NASA

SAFETY PERMIT

SAFETY AREA	8
PERMIT NO.	8-175
DATE ISSUED	1-15-78
EXPIRATION DATE	1-15-79
WORK UNIT NUMBER (TASK)	YOH 8845
REPLACES PERMIT NO.	8-156

LOCATION *(Room, building, cell, etc.)*

Off-Site
Clayton, New Mexico

DRAWING NOS.

CR 758662

(Affix color coded sticker here.)

TAKE ACTION
USE
Water, Dry Chemicals, or CO_2

ACTIVITY *(Describe research operation, facility equipment, etc., requiring safety approval.)*

Unattended automatic operation of the MOD-OA 200 kW Wind Turbine Generator

EMERGENCY CONTACT	HOME PHONE
(Knowledgeable person) John Sholes 419/	668-1104
(Alternate) John Collins 216/	777-4711

ACTIVITY APPROVED FOR SAFETY SUBJECT TO THE FOLLOWING CONDITIONS:

1. The MOD-OA WTG Start-up, Operation and Maintenance Procedure will be followed for the operation and maintenance of the MOD-OA WTG in an unattended automatic mode.

2. The City of Clayton Safety Plan for Operating a MOD-OA Wind Turbine shall be adhered to.

3. The conditions for personnel safety, as specified in Attachment A, shall be adhered to.

SAFETY APPROVAL REQUESTED BY
(Project Engineer's name)

John Sholes

AREA SAFETY COMMITTEE		ACTIVITY COMPLETED	
REVIEWED BY	APPROVED *(Chairman)*	DATE	SIGNATURE
Area 8	Original Signed by William J. Brown		

INSTRUCTIONS

Area Safety Committee Chairman

After approval of the Safety Permit Request *(NASA-C-923)*, complete this permit in accordance with procedures prescribed in LMI 1703.1 and send one copy to each of the following for:

CLEVELAND

Project engineer *(Resp. Eng.)*
Office of Environmental Health *(When applicable)*
Safety Office

PLUM BROOK

Lewis Safety Officer
Project engineer *(Resp. Eng.)*
Plum Brook Management Office

Project Engineer *(Responsible Engineer)*

1. Post a copy of this Permit, together with a copy of the Safety Permit Request and a copy of the Safety Permit Renewal Request *(when applicable)* at the location described.
2. Submit a new Safety Permit Request *(NASA-C-923)* at least 30 days prior to the expiration date if:
   a. the activity will not be completed by the expiration date;
   b. any change is made in conditions as described in this permit.
3. Submit a Safety Permit Renewal Request *(NASA-C-590)* at least 30 days prior to the expiration date if:
   a. the activity will not be completed by the expiration date
   b. no change is made to the operation as described in this Permit
4. When the activity is completed, remove this permit, indicate the completion date, and send it to the cognizant Area Safety Committee chairman.

NASA-C-919 (Rev. 6-77)

NASA-Lewis

Rev. #8
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ATTACHMENT A

Safety Permit B-175

1. The MOD-OA WTG site will be secured during nonwork periods to prevent exposure of hazards to personnel.

2. Personnel will not be allowed in the plane of rotation of the blades during initial rotation of the machine and until NASA is satisfied with 40 rpm operation. This exclusion area will be imposed at any time during machine operation if determined necessary by the City of Clayton and/or NASA.

3. Personnel shall not enter or perform work tasks in the nacelle unless the following conditions are met during the entire period personnel are in the nacelle:

a. The brake applied and system locked out by key switch.

b. The yaw system de-energized and secured.

c. The brake and yaw system keys shall be under control of the crew entering the nacelle.

d. Personnel entering the nacelle shall be in two-way radio communication with the site coordinator or his representative.

e. The minimum level of buddy system shall be the two-man system which is specified as follows:

TWO-MAN SYSTEM - refers to work situations where each of two or more persons present must be capable of detecting incorrect or unauthorized procedures with respect to the task to be performed. This does not require persons having equal knowledge, only the capability of detecting incorrect or unathorized procedures. In addition to performing their assigned operations, each man has the responsibility for checking the safe operation of the other(s).

4. Personnel entering the test site shall be under the control of the site coordinator or his authorized representative and obtain approval to proceed in a safe manner.

5. During windmill operation only authorized personnel under control of the site coordinator are allowed on the tower or the immediate vicinity of the tower. The two-man buddy system will be used or one man will have immediate communication with the test site coordinator. Personnel shall not be permitted on the tower during adverse weather conditions such as very high winds, icing and probable lightning conditions.

6. The nacelle will be equipped with a first aid kit, two 2-pound dry-type extinguishers and two Escape Scott (5 minute) Air Packs.

7. When the Hi-Ranger or Aerial Tower is used for blade inspection, the windmill will be placed under a controlled safe condition such that the blade inspection crew will not be subjected to a hazard from windmill operation.

8. Operation of the spider-shafter shall be subject to the following safety conditions.

a. Only trained, qualified operators shall be permitted to operate the spider-shafter.

b. During operation of the spider-shafter, a minimum of two qualified operators shall be present at the site.

c. Operation of the spider-shafter during adverse weather conditions, such as very high winds, icing and probable lightning, shall be prohibited.

d. During manned use of the spider-shafter, the operator shall have the ability to communicate with a ground operator or a person at another location for the purpose of summoning assistance in an emergency situation.

e. Personnel safety belts shall be worn in the spider-shafter.

f. Hard hats are required for personnel in the spider-shafter and ground personnel at the base of the tower.

g. An emergency plan shall be posted at the site which provides a plan for removal of an injured person from the nacelle and removal of personnel from the spider-shafter if it becomes inoperable.

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SAFETY PERMIT REQUEST

SAFETY COMMITTEE USE ONLY	DATE	Permit No.
	12/30/77	PREVIOUS
		NEW

TO: [ ] AREA SAFETY COMMITTEE NO. 8

EMERGENCY CONTACT	HOME PHONE
(Knowledgeable person) John Sholes	419-668-1104
(Alternate) John Collins	777-4711

FROM: PROJECT ENGINEER NAME *(Responsible Engineer)*	ORG. CODE	PAX	PBX	MAIL STOP
John Sholes	4030	8125	5100	49-6

1. ACTIVITY *(Describe research operation, facility, equipment, etc., requiring safety approval.)*

Operation of 200 kW Wind Turbine at Clayton, New Mexico

2. LOCATION *(Room, building, cell, etc.)*	3. DRAWING NOS.	4. WORK UNIT NO. *(Task)*
Clayton, NM	CR758662	YOH 8845

5. TESTS *(Nature of objectives, etc.)*

Synchronous Automatic Unattended Operation

6. EXPECTED DURATION DATES

START 1/7/78

COMPLETE 1/5/80

7. TEST RUNS

LENGTH: Continuous

TIME: [X] WORKDAY [X] NIGHT [X] WEEKEND

8. TEST CONDITIONS *(List the most hazardous conditions, use of fluids, power, radiation, etc.)*

MATERIAL, FLUID, ETC.	VOLTAGE, PRESSURE, ETC.	FREQUENCY, TEMPERATURE, ETC.	QUANTITY		REMARKS
			AT SITE	IN RIG	
Hydraulic Fluid	press	3000 psig	1500 psig	1500 psig	Operation 1500 psig Capability 3000 psig
Power	voltage	480 volts			
N_2 Gas	press	2000 psig		120 psig	Brake
N_2 Gas	press	1800 psig			Pitch Change

9. MATERIALS DESCRIPTION *("X" Blocks for materials to be used.)*

[ ] TOXIC
[ ] PYROPHORIC
[ ] CORROSIVE
[ ] RADIOACTIVE
[ ] MEDICAL MONITORING REQUIRED FOR PERSONNEL
[ ] EXPLOSIVE
[ ] OTHER *(Specify)* ______

10. DESCRIPTION OF RADIATION AND/OR RADIOACTIVE MATERIAL *(Complete and attach Users Radiological Training & Experience Record (NASA-C-197) for each user.)*

PHYSICAL FORM:
[ ] SEALED SOURCE
[ ] UNSEALED SOURCE
[ ] GAS
[ ] LIQUID
[ ] SOLID

TYPE OF RADIATION:
[ ] ALPHA [ ] GAMMA
[ ] BETA [ ] NEUTRON
[ ] OTHER *(Describe, if such as X-ray producing equipment.)*

ELEMENT OR COMPOUND ______
ELEMENT OR COMPOUND WEIGHT ______
RADIOACTIVE ISOTOPE ______
WEIGHT % RAD. ISO. IN ELEMENT/COMP. ______
ACTIVITY CURIES ______

11. RADIATION DETECTION INSTRUMENTS

INSTRUCTIONS: If required *(See **LMI 1703.1**)*, attach pertinent drawings, hazards analysis and/or Users and Experience Record *(NASA-C-197)*.

At Cleveland, send copy of this request with backup material as required to Office of Environmental Health. After completion of investigation and/or sign-off by OEH, Request shall be submitted to cognizant Area Committee Chairman Through the Requester.

At Plum Brook Station, send copy with backup material as required to the Plum Brook Management Office, and one copy of Request only to the Lewis Safety Office.

NASA-C-923 (Rev. 6-77)

MUST BE POSTED WITH SAFETY PERMIT

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12. IS THERE A PRECEDENT FOR THIS WORK? (If "Yes", give details.)	13. NASA-C-197 (attached) (Names)
[X] YES Plum Brook Mod-0 [ ] NO	[ ] YES [X] NO

14. DISCHARGE PRODUCTS *(Radioactive, corrosive, combustible, toxic and air/water pollution materials.)*

PRODUCTS: Temperature Radioactive, Noise, Toxic, Hazards *(Quantity or Degree)*	MEANS OF COPING WITH DISCHARGE PRODUCTS *(Abatement Device or Treatment Process)*	EFFLUENT DISCHARGED TO	SAMPLING FREQUENCY	TYPE OF DETECTION	MONITORING GROUP

15. SAFETY PRECAUTIONS *(Indicate what provision has been made for the following typical items.)*

SITUATION	SAFETY PRECAUTION
A. Ventilation	Fan available in nacelle Natural Ventilation
B. Detection of hazardous condition *(Radiation, toxicity, etc.)*	N/A
C. Ignition sources	None
D. Safe location of personnel during tests	Control Building
E. Avoidance of unsafe contamination of fuel or oxidant	N/A
F. "Fail-Safe" means in case of power, pressure, combustion or personnel failure	Blades feathered, brake applied
G. Protective means in case of over-temperature, over-pressure, or over-speed	Automatic shutdown
H. Accident Procedure *(Fire, explosion, spill)*	Hand Extinguishers
I. Collapse of vessel from evacuation	N/A
J. Personnel protection *(Protective clothing, breathing apparatus, medical check, etc.)*	N/A
K. Grounding	Machine is grounded; lightning protection is provided
L. Guarding of live parts	N/A
M. Shielding *(Radioactive material, radiation producing equipment, and high frequency radiation)*	N/A
N. Hazard – warning signs	Personnel not allowed on tower during operation
O. Level of buddy system	Two man team.

16. SPECIAL ITEMS *(List pertinent items peculiar to conditions of proposed test)*

This request includes use of permanent spider lift.

PROJECT ENGINEER (Signature)	DATE	REQUESTING DIVISION CHIEF (Signature)	DATE
John E. Shiles	12/22/77	W. H. Robbins	12/22/77
SUPERVISOR (Signature)		OFFICE OF ENVIRONMENTAL HEALTH (Signature)	DATE 12/22/77

NASA-C-923 (Rev. 6-77)

MUST BE POSTED WITH SAFETY PERMIT

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July 15, 1978

City of Clayton, New Mexico

Safety Plan for Operating a Mod-OA Wind Turbine

November 30, 1977

Submitted by:
Robert Johnson
City Manager

Rev. #8
July 15, 1978

TABLE OF CONTENTS

I. Introduction

The City of Clayton submits this safety plan to operate and maintain a Mod-OA Wind Turbine. The City Utility Department maintains a high level of training for its personnel and has an excellent record of safety over the years. Because of our isolation from other communities we perform all of our own maintenance on our electrical and mechanical equipment. We are very familiar with proper safety practices and maintaining both electrical and mechanical type equipment, and therefore feel confident of our ability to operate and maintain various types of generating equipment.

II. Discussion:

A. Site and Access: The Wind Turbine site consists of approximately 1/2-acre on city owned land currently being used as pasture land for cattle. The Wind Turbine installation consists of five main component groups: the ground test stand and its foundation, the Control Building, the tower and its foundation, the wind turbine assembly on top of the tower, and the transformer and oil reclosure. Figure B-1 illustrates a plot plan of the installation with a 6 foot high chain link fence installed around the two foundations to provide security against unauthorized entry. The fence will be seven feet away from the foundations and will be posted with signs identifying the installation as property of the U. S. Government (to be supplied by NASA). A four foot wide gate will provide authorized access, and the gate will be properly secured with a durable lock. Keys to the lock will be provided to the Clayton City Manager, the utility support team and NASA Mod-OA Project Manager.

The Control Building and lift at the top of the tower contain safety features which are a part of the Wind Turbine Safety System and are illustrated on NASA, Lewis Research Center Drawing Nos. CF-759027 and CF-760480. Unauthorized activation of these alarms will shut the Wind Turbine down.

B. Support Team: The City of Clayton Utility Department will provide a team of persons to manage the operation and maintenance of the Wind Turbine.

This team will not be dedicated totally to the Wind Turbine but will be selected individuals from our operations and maintenance personnel. The team will participate in the construction, installation and checkout of the Wind Turbine at Clayton. After the Wind Turbine is considered operational, responsibility for operating the machine will be assumed by the Utility Department.

The support team received approximately 40 hours of training at the Lewis Research Center in Cleveland on the Mod-OA Wind Turbine, acquiring specific details on the safe operation and maintenance of the machine.

The support team as well as other support personnel in the Utility Department are available "on-call" 24 hours a day, including weekends.

C. Area Responsibility: The City of Clayton will provide general liability insurance which will cover the operations of the Department of Energy, National Aeronautics and Space Administration, and the City of Clayton. The insurance policy shall be in the minimum amounts of $500,000 per person per accident.

D. Surveillance: The Wind Turbine site is located on the City of Clayton property and will be under the surveillance of the local city police via officers in patrol cars 24 hours a day. The police patrol generally will pass the Wind Turbine Site at least once per hour. During community celebrations and public events at the adjacent park and fairgrounds, the City Manager will provide what additional personnel are required to secure the Wind Turbine Site area. The existing barbed wire fence around the city property in which the Wind Turbine Site is located will be posted with "No Trespassing" signs, thus restricting and controlling access to the adjacent areas. Government personnel and their guests and Government authorized visitors must contact the City Manager for access to inspect the Wind Turbine.

E. Medical Facilities: The hospital in the City of Clayton has a capacity of 40 beds with 24 hour emergency room service. The City of Clayton Fire Department has in service an emergency accident vehicle and two ambulances manned by trained personnel. The fire station is manned 24 hours a day with qualified personnel trained for the proper use of these vehicles and associated equipment in the event of an emergency or accident.

F. Visitor Control: There will be a parking area adjacent to the existing barbed wire fence surrounding the city property on which the Wind Turbine is located for visitors to view the installation. The sign at the viewing area will direct visitors to the Tourist Information Building (Chamber of Commerce) on Highway 87, the main highway through town, to register and obtain free literature on the Wind Turbine. A sign will also be placed on Highway 87 next to the Tourist Information Building informing tourists and others that free information is available on the Wind Turbine at the Tourist Information Building. The three pamphlets to be furnished to the public will be provided by the U. S. Government.

G. Air Space Approval: The City of Clayton applied for FAA approval for the Wind Turbine installation and the FAA said no permit was required because of the adjacent radio tower (365 feet) and TV tower (380 feet).

H. Operation Procedures:

1. The NASA supplied "operating and maintenance procedures" will be used in operating and maintaining the Mod-OA wind turbine.

2. All Wind Turbine shutdowns will be reported to the designated individuals at NASA Lewis Research Center and documented as required by the operating procedures.

3. This Wind Turbine will be operated as specified in the Lewis Research Center Safety Permit.

I. Safety System: The Mod-OA Wind Turbine has an operational safety system designed to protect the machine itself and is described in NASA, Lewis Research Center Drawing No. CF-759027.

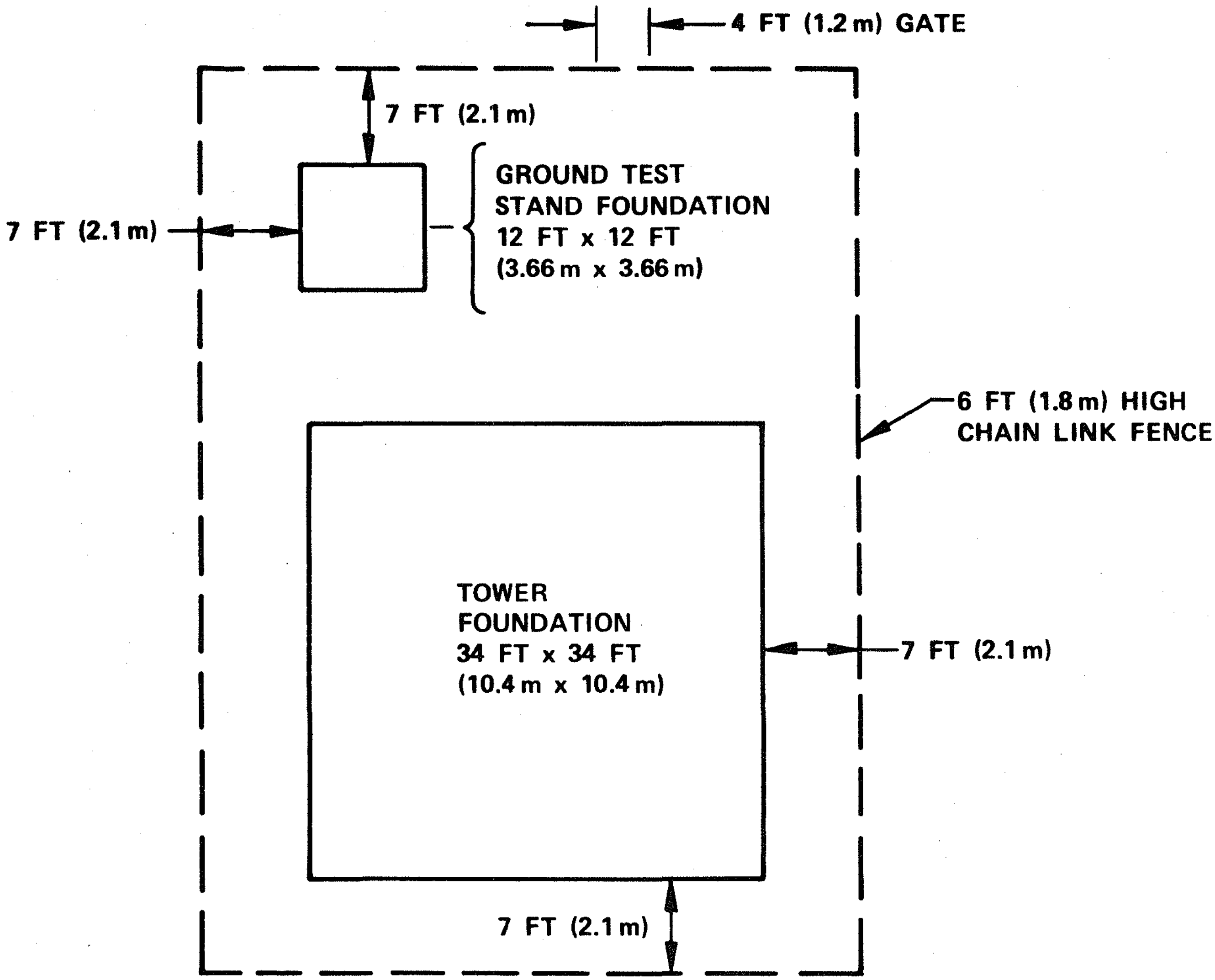

Figure B-1. Plot Plan for MOD-OA Wind Turbine at Clayton, NM.

EMERGENCY PLAN

PERSONNEL INJURY

In the event of personnel injury within the nacelle or tower, perform the following steps:

1. Determine the extent and type of injury and radio for ambulance aid.

2. Use the appropriate hoisting and/or lowering apparatus: Parachute harness or Hoistable stretcher.

3. Lower injured person into Spider-Shafter (manlift) with the aid of one person above and one person below the points of hoisting.

4. Once in the manlift descend to the ground using Spider-Shafter operating procedure.

5. After reaching the ground, help get the injured person out of the Spider-Shafter and into awaiting ambulance so hospital care can be rendered.

PERSONNEL RESCUE FROM INOPERATIVE SPIDER-SHAFTER

Perform the following rescue procedure:

1. Stranded person should radio contact ground personnel and lower rope located in shafter to ground.

2. Ground personnel to tie DESCENT MASTER (boatsman chair) which should be located in control building.

3. Stranded person hoist up DESCENT MASTER with the rope then once the DESCENT MASTER has been hoisted into the SHAFTER, use DESCENT MASTER to lower self to ground using the DESCENT MASTER operating procedure.

APPENDIX C

MOD-0A WIND TURBINE GENERATOR
PROGRAM LISTING

```
* DATASET: INTEL.CLAYTON
* DATE & TIME: 05/12/78 12:12:41
        DECLARE (VEL$L,VEL$H,POWER$L,POWER$H) BYTE;
        DECLARE (POS$L,POS$H,METVEL$L,METVEL$H) BYTE;
        DECLARE ( RAMPCTL,NOSYNC,PFLAG,DEBOUNCE) BYTE;
        DECLARE (POSCMD$L,POSCMD$H,RPM$L,RPM$H) BYTE;
        DECLARE (FREQ$L,FREQ$H,WINDTMR,SLOWSTART) BYTE;
        DECLARE (RPMCMD$L,RPMCMD$H) BYTE;
        DECLARE (SFLAG,RFLAG,DFLAG) BYTE;
        DECLARE (SSPOUT,REEDOUT,SYNCFLAG,RUNOUT,RSTFLAG) BYTE;
        DECLARE (SYNCTMRFLAG,PUMPTMRFLAG,I,EFLAG) BYTE;
        DECLARE (VEL$POINTER,POWER$POINTER,FREQ$POINTER) ADDRESS;
        DECLARE (RPM$POINTER,RPMSET,RPMCMD$POINTER) ADDRESS;
        DECLARE (VELCLAMP,PWRCMD,POS$POINTER) ADDRESS;
        DECLARE (POSCMD$POINTER,METVEL$POINTER) ADDRESS;
        DECLARE VEL BASED VELPOINTER ADDRESS;
        DECLARE POWER BASED POWER$POINTER ADDRESS;
        DECLARE FREQ BASED FREQ$POINTER ADDRESS;
        DECLARE POSCMD BASED POSCMD$POINTER ADDRESS;
        DECLARE RPM BASED RPM$POINTER ADDRESS;
        DECLARE RPMCMD BASED RPMCMD$POINTER ADDRESS;
        DECLARE POS BASED POS$POINTER ADDRESS;
        DECLARE METVEL BASED METVEL$POINTER ADDRESS;
/* INTERRUPT #0 */
        STARTUPPOINTER: PROCEDURE INTERRUPT 0;
        OUTPUT(47)=0B;
        RUNOUT=0B;
        OUTPUT(25)=RUNOUT;
  /* SET INTERRUPT MASK */
        OUTPUT(10)=11011101B;
        ENABLE;
        RSTFLAG=1;  EFLAG=0;
        RPMSET=3687;
    /* SET ALL TIMERS */
        OUTPUT(24)=0;
        OUTPUT(24)=3770;
        RAMPCTL=0; SLOWSTART=0; NOSYNC=0;
        OUTPUT(30)=10111111B;
        VEL$POINTER=.VEL$L;
        POWER$POINTER=.POWER$L;
        FREQ$POINTER=.FREQ$L;
        POSCMD$POINTER=.POSCMD$L;
        RPM$POINTER=.RPM$L;
        RPMCMD$POINTER=.RPMCMD$L;
        POS$POINTER=.POS$L;
        METVEL$POINTER=.METVEL$L;
        GOTO SHUTDOWN;
        END STARTUPPOINTER;
    STARTPOINTER: PROCEDURE INTERRUPT 1;
   /* SET INTERRUPT MASK */
        OUTPUT(10)=10010010B;
         DFLAG=1;
         RSTFLAG=0;
        EFLAG=0:
        REEDOUT=REEDOUT OR 01000000B;
        OUTPUT(30)=REEDOUT;
```

```
        RUNOUT=00010000B;
        OUTPUT(47)=0B;
        END STARTPOINTER;
    /* INTERRUPT #2 */
   STOPPOINTER: PROCEDURE INTERRUPT 2;
   /* SET INTERRUPT MASK */
        OUTPUT(10)=10010100B;
        DFLAG=0;
        REEDOUT=REEDOUT AND 10111111B;
        OUTPUT(30)=REEDOUT;
   OUTPUT(47)=0B;
        RUNOUT=00100000B;
        END STOPPOINTER;
   /* INTERRUPT #3 */
   EMERGPOINTER: PROCEDURE INTERRUPT 3;
   /* SET INTERRUPT MASK */
        OUTPUT(10)=11111110B;
        REEDOUT=REEDOUT AND 10111111B;
      OUTPUT(30)=REEDOUT;
        EFLAG=1;
        RUNOUT=RUNOUT AND 00001111B;
        RUNOUT=RUNOUT OR 00110000B;
        OUTPUT(47)=0B;
        END EMERGPOINTER;
   /* INTERRUPT #5 */
      REMOTESTARTPOINTER: PROCEDURE INTERRUPT 5;
   /* SET INTERRUPT MASK */
        OUTPUT(10)=10110010B;
        DFLAG=1;
        RSTFLAG=0; EFLAG=0;
        REEDOUT=REEDOUT OR 01000000B;
        OUTPUT(30)=REEDOUT;
        RUNOUT=01010000B;
        OUTPUT(25)=RUNOUT;
        OUTPUT(47)=0B;
        END REMOTESTARTPOINTER;
   /* INTERRUPT #6 */
        REMOTESTOPPOINTER: PROCEDURE INTERRUPT 6;
     /* SET INTERRUPT MASK */
        OUTPUT(10)=11010000B;
        DFLAG=0;
        REEDOUT=REEDOUT AND 10111111B;
        OUTPUT(30)=REEDOUT;
        RUNOUT=01100000B;
        OUTPUT(25)=RUNOUT;
        OUTPUT(47)=0B;
        END REMOTESTOPPOINTER;
   /* INTERRUPT #7 */
        SPAREPOINTER: PROCEDURE INTERRUPT 7;
        OUTPUT(47)=0B;
        RUNOUT=01110000B;
        OUTPUT(25)=RUNOUT;
        END SPAREPOINTER;
    /* WATCHDOG TIMER #8 */
```

```
RESTART:  OUTPUT(24)=01111111B;
          OUTPUT(24) = 377Q;
          IF RSTFLAG=1 THEN GOTO SHUTDOWN;;
          OUTPUT(25)=RUNOUT;
          ENABLE;
      /* CHECK PWR STATION BREAKER AND ROTOR BRAKE */
          IF (INPUT(17) AND 102Q)=102Q THEN GOTO WIND$CHECK;
          RUNOUT=RUNOUT AND 11110000B;
          RUNOUT=RUNOUT OR 00000111B;
          GOTO EMERGENCY;
      /* STORE WIND VELOCITY, +5V=100 MPH=1023 */
WIND$CHECK: OUTPUT(21)=1B;
      /*  MUX SETTLING TIME  */
          OUTPUT(21)=00000001B;
          OUTPUT(22)=0B;
      /*  A/D CONVERT TIME >50USEC  */
          CALL TIME (1);
          VEL$L=INPUT(20);
          VEL$H=INPUT(19) AND 00001111B;
      /* STORE MET TOWER WIND VELOCITY BASIS 10V=100MPH */
          OUTPUT(21)=00000111B;
      /* MUX SETTLING TIME */
          OUTPUT(21)=00000111B;
          OUTPUT(22)=0B;
      /* A/D CONVERT TIME > 50 USEC */
          CALL TIME(1);
          METVEL$L=INPUT(20);
          METVEL$H=INPUT(19) AND 00001111B;
          IF EFLAG=1 THEN GOTO EMERGENCY;
      /* SHUTDOWN IF MET TOWER WIND VEL > 45 MPH */
          IF RFLAG=0 THEN GOTO BUG2;
          IF METVEL<2969 THEN GOTO BUG2;
          DFLAG=0;
          RUNOUT=RUNOUT AND 11110000B;
          RUNOUT=RUNOUT OR 00001001B;
          REEDOUT=REEDOUT AND 10111111B;
      BUG2:IF SFLAG=1 THEN GOTO SHUTDOWN;
      /* CHECK DISPATCHER RUN STATUS */
          IF DFLAG=0 THEN GOTO SHUTDOWN;
      /* CHECK FOR FAVORABLE WIND CONDITIONS,+5V=100MPH=1023 */
      /* IS VEL > 40MPH */
         IF VEL>2457 THEN GOTO BUG6;
     /* IS VEL>35 MPH? */
          IF VEL>2411 THEN GOTO BUG10;
     /* IS VEL > 13 MPH */
    IF VEL > 2181 THEN GOTO BUG5;
      /* IS VEL < 10MPH */
   IF VEL <2150 THEN GOTO BUG6;
   IF (RFLAG=1) THEN GOTO BUG5;
          GOTO ILLWIND;
     BUG6: IF WINDTMR=1 THEN GOTO BUG4;
          WINDTMR=1;
     /* START TIMER #0 */
          OUTPUT(24)=11111110B;
```

```
            OUTPUT(24)=377Q;
    /* HAS TIMER #0 TIMED OUT? */
    BUG4: IF (INPUT(18) AND 1)=1 THEN GOTO CONTX;
            GOTO ILLWIND;
    BUG10: IF RFLAG=0 THEN GOTO BUG6;
    BUG5: WINDTMR=0;
     /* ENERGIZE PUMP */
          CONTX:RUNOUT=RUNOUT AND 11110000B;
            RFLAG=1;
             SSROUT=SSROUT AND 11111110B;
            OUTPUT(28)=SSROUT;
     /* COMPARE PUMP STATUS WITH HYD PRESSURE */
            IF( INPUT(17) AND 1)=1 THEN GOTO ADVANCE;
            IF RFLAG=1 THEN RUNOUT=RUNOUT OR 00000010B;
   IF RFLAG=1 THEN GOTO EMERGENCY;
     /* IF PUMP PRESS. DOES NOT APPEAR WITHIN 2 MIN.,CRASH */
            IF PUMPTMRFLAG=1 THEN GOTO CONTPUMP;
    /* START TIMER #2 */
            OUTPUT(24)=11111011B;
            OUTPUT(24)=377Q;
            PUMPTMRFLAG=1;
    /* IS TIMER #2 TIMING? */
      CONTPUMP: IF (INPUT(18) AND 40Q)=40Q THEN GOTO RESTART;
            RUNOUT=RUNOUT AND 11110000B;
            RUNOUT=RUNOUT OR 00000010B;
            GOTO EMERGENCY;
  ADVANCE: IF DEBOUNCE>250 THEN GOTO BUG8;;
            DEBOUNCE=DEBOUNCE+1;
            GOTO BUG9;
    BUG8: PFLAG=1;
     /* ENERGIZE FAILSAFE VALVE */
            BUG9: SSROUT= SSROUT AND 11111101B;
            OUTPUT(28)= SSROUT;
     /* CHECK MODE OF PITCH CONTROLLER */
            IF (REEDOUT AND 10000000B)=10000000B THEN GOTO PITCH;
     /* CHECK FOR PITCH CONTROLLER RPM ERROR */
   IF (INPUT(17) AND 40Q)=40Q THEN GOTO SETPTRPM;
            IF SYNCFLAG=1 THEN GOTO SETPTRPM;
            RUNOUT=RUNOUT OR 00000011B;
    BUG50: SLOWSTART=SLOWSTART+1;
            IF SLOWSTART<4 THEN GOTO BUG3;
            REEDOUT=REEDOUT AND 10111111B;
            RFLAG=0;
    BUG3: SFLAG=1;
            GOTO RESTART;
     /* ADDRESS MULTIPLEXER FOR PITCH ANGLE */
  SETPTRPM: OUTPUT(21)=00000011B;
     /*  MUX SETTLING TIME   */
            OUTPUT(21)=00000011B;
          OUTPUT(22)=0B;
     /*  A/D CONVERT TIME >50USEC   */
            CALL TIME (1);
            POSCMD$L=NOT INPUT (20);
            POSCMD$H=NOT(INPUT(19) OR 11110000B);
```

```
    /* MAKE CONTROLLER TRACK PITCH ANGLE */
        OUTPUT(32)=NOT POSCMD$L;
        OUTPUT(33)=NOT(POSCMD$H OR 11110000B);
        IF RPMCMD>=(RPMSET-82) THEN GOTO FIELD;
BUG49: IF RPMCMD>=RPMSET THEN GOTO SYNC;
    /* HAS TIMER #4 TIMED OUT */
 IF (INPUT(18) AND 20Q)=20Q THEN GOTO RESTART;
        IF RAMPCTL<SLOWSTART THEN GOTO BUG25;
        RPMCMD=RPMCMD+1;
        RAMPCTL=0;
        GOTO BUG26;
  BUG25: RAMPCTL=RAMPCTL+1;
 BUG26:OUTPUT(32)=NOT RPMCMD$L;
        OUTPUT(34)=NOT(RPMCMD$H OR 11110000B);
    /* START TIMER #4 */
        OUTPUT(24)=11101111B;
        OUTPUT(24)=377Q;
        GOTO RESTART;
    /* TURN ON FIELD CURRENT */
FIELD: SSROUT=SSROUT AND 11111011B;
        OUTPUT(28)=SSROUT;
        GOTO BUG49;
    /* READ RPM */
PITCH: OUTPUT(21)=00000000B;
    /*  MUX SETTLING TIME  */
        OUTPUT(21)=00000000B;
       OUTPUT(22)=0B;
    /*  A/D CONVERT TIME >50USEC  */
        CALL TIME (1);
        RPM$L=INPUT(20);
        RPM$H=INPUT(19) AND 00001111B;
    /* TEST IF RPM IS GREATER THAN 6, BASIS +5V=50RPM */
         IF RPM > 2169 THEN GOTO TRANSFER;
    /* RAMP AT 2 DEG/SEC TO -55 DEG */
        IF POSCMD>2663 THEN GOTO BUG30;
        IF (INPUT(18) AND 20)=20 THEN GOTO RESTART;
        POSCMD=POSCMD+4;
        GOTO BUG32;
  BUG30:IF (INPUT(18) AND 20)=20 THEN GOTO RESTART;
        IF RAMPCTL<SLOWSTART THEN GOTO BUG31;
        POSCMD=POSCMD+1;
        RAMPCTL=0;
        GOTO BUG32;
  BUG31:RAMPCTL=RAMPCTL+1;
    /* LIMIT MANUAL POSITIONING TO -20 DEGREES */
    /* -90 DEGREES(FEATHER) TO +10 DEGREE (POWER)= 0 TO +10V */
  BUG32:IF POSCMD >= 3500 THEN RUNOUT=RUNOUT OR 00000110B;
        IF POSCMD >= 3500 THEN GOTO BUG50;
    /* MOVE BLADE PITCH */
        OUTPUT(32)=NOT POSCMD$L;
        OUTPUT(33)=NOT(POSCMD$H OR 11110000B);
    /* START TIMER#1 */
        OUTPUT(24)=11111101B;
        OUTPUT(24)= 377Q;
```

```
        GOTO RESTART;
TRANSFER: RPMCMD=2290;
        OUTPUT(32)=NOT RPMCMD$L;
        OUTPUT(34)=NOT (RPMCMD$H OR 11111000B);
    /* TRANSFER TO AUTO */
        REEDOUT = REEDOUT AND 01000000B;
        OUTPUT(30)= REEDOUT;
        GOTO RESTART;
    /* SYNCHRONIZATION */
SYNC: RPMCMD=RPMSET;
        OUTPUT(32)=NOT RPMCMD$L;
        OUTPUT(34)=NOT (RPMCMD$H OR 11111000B);
        SSROUT=SSROUT AND 11110111B;
        OUTPUT(28)= SSROUT;
        IF SYNCTMRFLAG=1 THEN GOTO CONTSYNC;
    /* SET SYNC TIMER #5 */
        OUTPUT(24)=11011111B;
        OUTPUT(24)=377Q;
         SYNCTMRFLAG = 1;
CONTSYNC: IF (INPUT(17) AND 40Q)=40Q THEN GOTO PWRCONTROL;
        IF SYNCFLAG=1 THEN PUNOUT=PUNOUT OR 00000100B;
        IF SYNCFLAG=1 THEN GOTO EMERGENCY;
    /* TRY TO SYNCHRONIZE FOR ONE MINUTE ONLY */
    /* IS TIMER #5 TIMING */
        IF (INPUT(18) AND 40Q)=40Q THEN GOTO RESTART;
        PUNOUT=PUNOUT OR 00000101B;
        NOSYNC=NOSYNC+1;
        IF NOSYNC<4 THEN GOTO BUG7;
        DFLAG=0;
        REEDOUT=REEDOUT AND 10111111B;
  BUG7: SFLAG=1;
        GOTO RESTART;
  PWRCONTROL: IF SYNCFLAG=1 THEN GOTO NODELAY;
   /* TWO SECOND DELAY TO CONFIRM SYNC*/
         DO I= 1 TO 50;
        CALL TIME(250));
  /* RESET WATCHDOG TIMER #7*/
        OUTPUT(24)=01111111B;
        OUTPUT(24)=377Q;
        END;
        IF(INPUT(17) AND 40Q)=40Q THEN GOTO SETSYNCFLAG;
        GOTO RESTART;
SETSYNCFLAG: SYNCFLAG=1;
         SLOWSTART=0; NOSYNC=0;
    /* CHANGE TO POWER CONTROL COMPENSATION */
 NODELAY: REEDOUT=REEDOUT OR 01110000B;
        OUTPUT(30)=REEDOUT;
    /* SET POWER SETPOINT=200KW */
        PWRCMD=3412;
        OUTPUT(32)=NOT LOW(PWRCMD);
        OUTPUT(34)=NOT (HIGH(PWRCMD) OR 11111000B);
        GOTO RESTART;
  LLWIND: PUNOUT =PUNOUT AND 11110000B;
        PUNOUT=PUNOUT OR 00001000B;
```

```
SHUTDOWN: REEDOUT=REEDOUT AND 11001111B;
          REEDOUT=REEDOUT OR 10000000B;
          OUTPUT(30)= REEDOUT;
          OUTPUT(25)=RUNOUT;
          RFLAG=0;
          SFLAG=1;
     /* READ POWER,+10V=300KW */
         OUTPUT(21)=00000100B;
     /*  MUX SETTLING TIME  */
          OUTPUT(21)=00000100B;
          OUTPUT(22)=0B;
     /*  A/D CONVERT TIME >50USEC   */
          CALL TIME (1);
          POWER$L=INPUT(20);
          POWER$H=INPUT(19) AND 00001111B;
     /* DESYNCHRONIZE AT OKW */
          IF POWER <=2100 THEN GOTO DESYNC;
    /* ARE BLADES FEATHERED? */
    FEATHER: OUTPUT(21)=00000010B;
    /* MUX SETTLING TIME */
          OUTPUT(21)=00000010B;
          OUTPUT(22)=0B;
    /* A/D CONVERT TIME > 50 USEC */
          CALL TIME(1);
          POS$L=INPUT(20);
          POS$H=INPUT(19) AND 00001111B;
          IF POS<=2100 THEN GOTO OFF;
     /* IS TIMER #3 TIMING */
 IF (INPUT(18) AND 100)=100 THEN GOTO RESTART;
     /* DECREMENT PITCH ANGLE */
 POSCMD=POSCMD-1;
          IF POSCMD <2049 THEN POSCMD=2049;
          OUTPUT(32)=NOT POSCMD$L;
          OUTPUT(33)=NOT (POSCMD$H OR 11110000B);
     /* START TIMER #3 */
          OUTPUT(24)=11110111B;
          OUTPUT(24)=377Q;
          GOTO RESTART;
EMERGENCY: SSROUT=SSROUT OR 00000010B;
          OUTPUT(28)=SSROUT;
      /* RESET POSITION COMMAND TO FEATHER */
           POSCMD = 2049;
          OUTPUT(32)=NOT POSCMD$L;
          OUTPUT(33)=NOT (POSCMD$H OR 11110000B);
          EFLAG=1;
          GOTO SHUTDOWN;
     /* DEENERGIZE PUMP,VALVE */
OFF: SSROUT=SSROUT OR 00001111B;
          OUTPUT(28)= SSROUT;
     /* RESET FLAGS AND GAIN */
          PWRCMD = 3412;
          PUMPTMRFLAG=0;
          SFLAG=0; SYNCTMRFLAG=0;
          PFLAG=0; DEBOUNCE=0;
```

```
        SYNCFLAG=0;
        WINDTMR=1;
        POSCMD =2049;
        OUTPUT(32)=NOT POSCMD$L;
        OUTPUT(33)=NOT (POSCMD$H OR 11110000B);
        CALL TIME (10);
     /* SCALING +1CV = 50RPM */
        RPMCMD = 2290;
        OUTPUT(32)= NOT RPMCMD$L;
        OUTPUT(34)= NOT (RPMCMD$H OR 11111000B);
        IF EFLAG=1 THEN GOTO HALTX;
        GOTO RESTART;
HALTX: REEDOUT = REEDOUT AND 10111111B;
        OUTPUT(30)= REEDOUT;
        OUTPUT(25)=PUNOUT ;
        HALT;
     /* DROP CB1,CB2,SYNCCMD AND FIELD CONTACTOR */
DESYNC: SSROUT=SSROUT OR 00001100B;
        OUTPUT(28)=SSROUT;
        GOTO FEATHER;
EOF
```

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16. Abstract

This report documents the design, analysis, and initial performance of the MOD-OA 200 kW wind turbine generator at Clayton, NM. The MOD-OA was designed and built by the NASA Lewis Research Center for the U.S. Department of Energy to obtain operation and performance data and experience in utility environments. This report covers the effort from 1975 to March 1978, when the MOD-OA was released to the Clayton utility for operation. This report discusses the project requirements, approach, system description, design requirements, design, analysis, system tests, installation, safety considerations, failure modes and effects analysis, data acquisition, and initial performance for the wind turbine.

The design and analysis of the components and systems are presented. These are the rotor, drive train, nacelle equipment, yaw drive mechanism and brake, tower, foundation, electrical system, and control systems. The rotor includes the blades, hub, and pitch change mechanism. The drive train includes the low speed shaft, speed increaser, high speed shaft, and rotor brake. The electrical system includes the generator, switchgear, transformer, and utility connection. The control systems are the blade pitch, yaw, and generator control, and the safety system. Manual, automatic, and remote control are discussed. Systems analyses on dynamic loads and fatigue are presented.

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